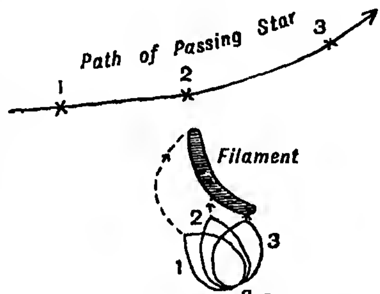
that the tidal disruption led to the ejection of small jets of solar matter to great distances, the passing star drawing them forward in the line of its own motion. Within the ejections larger nuclei gathered together, and these, by degrees, collected in themselves the smaller scattered bodies or planetesimals and eventually grew into the mature planets of the system. This theory, only briefly sketched here, carried with it certain definite corollaries as to the constitution of the earth. It was not necessary to assume that the earth as a whole was ever in a molten condition. It grew from small beginnings by the addition of planetesimal matter, rapidly at first, but with decreasing speed. Internal heat arose from condensation in its mass during the period of growth, and molten pockets of the more readily fusible constituents were formed and forced outwards, leading to the differentiation between a stony "crust" and a metallic interior. The materials of the atmosphere and the oceans, no less than those of the lithosphere itself, have, on this theory, to be regarded as derived from the planetesimals.



[After Jeans.

FIG. 2.—TIDAL DISRUPTION OF THE SUN. Jet or filament of gaseous matter detached from the sun.

Other tidal theories.—The planetesimal hypothesis, like its famous predecessor, has suffered criticism on many grounds, though its root principle is now generally accepted. Other versions of the origin of the solar system have been put forward in recent years by Jeans and by Jeffreys. In these the possible eruptive tendencies within the sun are left out of account, its disruption being assigned to tidal effects alone. It is claimed that if a passing star, several times more massive than the sun, came within a certain limiting distance, the sun itself might be literally broken up by the intense tidal forces generated and that jets of solar matter would be thrown out (Fig. 2). These would be of sufficient substance to hold together without appreciable scattering and, under gravity, knots or condensations would form in these jets, like drops in a jet of water. These knots would in time become independent planets, all of the same age, each revolving round the sun

in a nearly circular orbit. Such a tidally ejected mass would be thickest in the middle, tapering off to the two ends, and the larger separate masses would occur in the middle of the sequence, the smaller planets towards the extremities. This fits the facts of the solar system well—the two giant planets, Jupiter and Saturn, occupying a central position in the sequence (Fig. 1). It is further supposed that the planets, under the influence of the attraction of the sun and possibly also of the disturbing star itself, would give birth to satellites, a limit to the process being reached when the newly-born smaller bodies could not hold together under their own gravitation. The smaller planets and satellites are not regarded as formed by slow condensation from the gaseous state, for they could have held together only by partial liquefaction or solidification soon after their birth, thus restraining the diffusion of their material into space. In the case of these bodies a liquid core would almost immediately be formed, partly by cooling caused by expansion of the gases and partly by radiation from the surface. In this way the earth is held to have cooled down until it was completely liquid and, thereafter, through loss of heat by radiation, to have solidified, its materials becoming in the process zoned in the order of their densities. According to Jeffreys all these changes were probably accomplished within quite a brief period. While the earth was fluid the heat supplied by convection to its surface would almost keep pace with the loss by radiation, but upon the formation of a crust, only the slow processes of conduction could convey heat to the surface, whose temperature would rapidly fall. Aqueous vapour, if present in the primeval atmosphere, would condense almost as soon as the solid crust was formed and thus the normal processes of denudation and surface differentiation could be initiated.

The tidal hypotheses of cosmogony all require the co-operative action of two stars. We are here concerned with cosmogony only in so far as it deals with the origin of the earth; the prior question of stellar cosmogony need not be considered. It is, however, of interest to note that, in addition to the points of light which are stars,[1] there

[1] It is not intended to convey that a star is a geometrical point, though until recently no test could differentiate any star from such a point. In 1920, however, Michelson was able to show that the star Betelgeuse had a diameter of not less than 200 million miles. The orbit of the earth could be placed entirely inside it.

exist other objects in the heavens, the nebulæ, distinguishable from stars because they cover a measurable area of the sky. These nebulæ represent matter in its most luminous and tenuous state. Their configurations and their spectra show that they are masses of gas enormously larger than the nebula imagined by Laplace, and perhaps to be regarded as distinct stellar systems. They undergo an evolutionary sequence of changes as their speed of rotation increases with shrinkage. Under the combined influence of rotation and the attraction of neighbouring nebulæ, the equatorial belt is drawn out into two long arms, arranged antipodally, such as are typically displayed in the "spiral nebulæ." Within these arms the matter shed from the central body becomes gathered in distinct "knots." Such condensations are regarded as being approximately as massive as the largest stars, and are in fact to be regarded as newly born stars. The processes taking place in the spiral nebulæ thus are somewhat analogous to those now believed to have been concerned in the origin of the solar system. The products of the process, however, are not planets but stars, and we cannot, as has been suggested, regard spiral nebulæ as giving a distant working demonstration of the origin of the solar system.

CHAPTER II

THE CONSTITUTION OF THE EARTH'S INTERIOR

Introductory.—The interior of the earth, or at least those portions beyond the range of direct observation, fall outside the domain of geography and even of geology. Nevertheless our understanding of surface conditions must depend, in part, on our view of the constitution of the earth-ball as a whole.

The greater part of the continental surfaces is covered by sedimentary rocks, reaching in places a thickness of several miles; but the average thickness of the sedimentary cover, regarded as spread uniformly over the continents, would probably not exceed half a mile, an insignificant figure. Below the sediments, observation records crystalline rocks at many places and such rocks actually emerge over considerable tracts, as in the great "shields" of Canada, the Baltic area, North Eastern Asia, Western Australia, Peninsular India, Central Africa, and Brazil. The density of these crystalline rocks, as a whole, is less than 3, though certain heavier varieties are known with densities ranging up to 3·5 approximately. From these facts we may make our first deduction as to the interior of the earth. The density of the earth as a whole is 5·5, the average density of exposed rock masses less than 3, whence we conclude that the density of the central core must be high, and that, in fact, it consists of matter probably 7 or 8 times as heavy as water. On first consideration it might be supposed that this high density was due solely to the vast pressures which must prevail in the central region. Experiment demonstrates the inadequacy of this hypothesis, for both rocks and metals reveal a very definite limit beyond which their density cannot be increased by pressure, and the density of the interior region is too high to be wholly explained in this way. We are thus led to conclude that the materials of the core are intrinsically heavy, and, largely if not exclusively, metallic in their nature. A number of considerations favour the hypothesis that the core is made of a nickel-iron mixture, similar to that which forms the metallic meteorites. This view is consonant with the rigidity of

the earth-ball, which is somewhat less than that of steel; and it clearly has a possible bearing on the earth's magnetism, since iron and nickel are amongst the most highly magnetic elements. Surrounding the metallic core is a zone of rock materials, of which the upper part at least is crystalline. Its separation from the metallic nucleus must have been akin to the separation of slag from metal in the smelting of iron, and clearly implies that though the earth now behaves as a solid body, it has passed through a liquid phase.

With these general ideas in mind we may pass on to consider in more detail the probable physical state and chemical constitution of the several parts of the earth's interior. The increase of temperature with depth at an average rate of 1° C. per 32 metres, clearly points to the prevalence of high interior temperatures. It was this fact, taken with the evidences of eruption of molten rock in volcanoes, which led formerly to the erroneous view of a thin solid crust on a liquid core. The fact that the earth behaves as a solid, in respect of tidal stresses and of the passage of earthquake waves through the earth's interior to distant points, compelled the abandonment of this idea, and it became clear that the pressure factor had been omitted from consideration. Though a continuance of the observed temperature gradient would result, at a depth of a few miles, in temperatures above the laboratory melting points of most rocks and metals, pressure raises the melting point of these substances and would be effective in maintaining a solid state in spite of the temperature. In the latter part of the nineteenth century a compromise was suggested, which envisaged a core kept solid by pressure, and a cooled solidified crust, with an intervening liquid zone from which molten lava might pass to the surface. This idea bears some semblance to others now current, which regard the earth as having been periodically in this state in the past, and fated inevitably to return to it in the future. On the other hand, it has been pointed out that experiment indicates a "critical point" beyond which, with rising temperature, no pressure, however great, can suffice to maintain a substance in a solid or even a liquid state, and that, for this reason, the earth's inmost parts must be in a gaseous condition. The suggestion has little relevance for students of surface forms and effects, for the material would not be a "gas" in the sense in which the word is used on the

surface of the earth; it might be expected to possess wholly unfamiliar properties, including high rigidity.

Many of the questions at issue cannot be adequately handled, nor can safe conclusions be drawn, until much more experimental work has been done under high temperature and pressure conditions. It is important to bear in mind that experiments at atmospheric pressure give no safe measure of the properties and behaviour of substances in depth and that, as suggested above, the normal connotations of the words "solid," "liquid" and "gas" must not be taken to apply in this case. It is within our experience, even under surface conditions, that some substances share the properties of both solids and liquids. Thus pitch and sealing wax are "solid" and brittle under a sudden heavy blow, but liquid under the long continued smaller stresses imposed by a weight, which will sink into the mass. This analogy is useful in thinking of the sub-surface condition of the earth; it should not, however, be applied crudely or carried too far.

We may content ourselves with the following limited conclusions regarding the physical state of the interior:

(1) That the earth, as a whole, behaves as a solid ball, at least to suddenly imposed stresses;

(2) That its more superficial shells can "flow," or behave like viscous liquids, under suitable conditions; and

(3) That portions of the under layer can become liquid, either through relief of pressure or access of heat, and thus give rise to the phenomena of vulcanicity.

As regards the chemical constitution of the outer rock-shell, we know that its crystallized portions consist mainly of silicates, such as the common minerals felspar, mica, etc. In view of the fact that the known rock-forming silicates vary considerably in density and that the crystalline rocks fall into two fairly clearly marked categories, one mainly composed of the specifically lighter silicates, the other of the denser types, it has long been surmised that the rock shell may be divided into two parts. The study of artificially melted rock materials shows that the heavier crystals formed on cooling tend to sink, and many bodies of igneous rock exposed at the earth's surface give clear evidence of a downward concentration of the heavier constituents. In this we see the results of small scale repetitions of a process which must have operated generally during the earth's molten stage.

As we shall show in the sequel, facts of geological

observation and many geophysical arguments combine to support the suggestion of Suess that we have beneath the sedimentary cover of the continents, first, a layer of material comparable in composition with ordinary granite, and called by him the "*sal*" (better written *sial*); and, beneath, a thicker layer, the *sima*, of higher density, comparable in composition with the heavier (basic and ultra-basic) igneous rocks. This general conception has latterly received wide assent from students of geophysics. The conclusion was reached on general grounds and can be justified by many purely geological arguments, but a much higher element of precision has been rendered possible by the findings of seismology, to which we may now turn.

The evidence of seismology.—In the foregoing paragraphs we have sketched in outline a picture of the earth's metallic nucleus and the surrounding rock shells, without discussing the extent of the several parts and their relation to one another. Almost the only direct evidence on these points is obtained from the records of earthquakes, the observation and interpretation of which constitute the important and growing science of seismology.

If we exclude the small and local shocks associated with volcanic eruptions, the collapse of underground caverns and major landslips, all earthquakes are due to "earth-movement" in the strict sense of the term. Stresses may gather in the crust in a number of possible ways, reviewed later, and thus lead either to slow "rock-flow," kindred to the creeping motion of a glacier, to folding or to definite fracture (faulting). Though the actual movement along a plane of fracture is generally small, vibrations or waves are caused by the grinding friction of the two moving rock-masses and these waves travel out in all directions from the point of origin, or seismic focus. The immediate and spectacular effects of the shock are felt round about the epicentre, the point on the earth's surface vertically above the focus. The waves generated by friction may, however, travel for great distances through the crust and the interior regions of the earth. It is convenient, as with light waves, to speak of the actual paths followed by the waves as "rays."

A solid body can transmit two distinct types of waves—longitudinal, primary or P waves, analogous to those of sound, in which the particles move both to and fro in the line of the ray; and transverse, secondary or S waves,

analogous to water ripples or light waves, in which particles move at right angles to the ray. In addition, it is possible to set up waves in a solid body which affect only its surface regions, dying out at a small depth below. These surface waves include two varieties, and are generally referred to as L waves in seismological literature. The existence of these three definite varieties of waves associated with earthquake shocks was predicted on theoretical grounds before they were actually observed. Their existence was definitely recognized in earthquake records in 1900.

The seismograph, by the aid of which distant shocks are recorded, consists essentially of a rigid beam, suspended horizontally, fixed at one end to a pillar, while the other end is free to move in a horizontal plane. Combinations of instruments can be arranged to record the north–south, the east–west, and the up and down movements of the

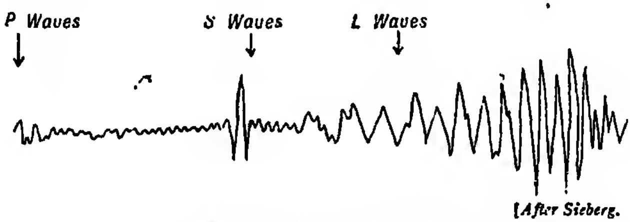
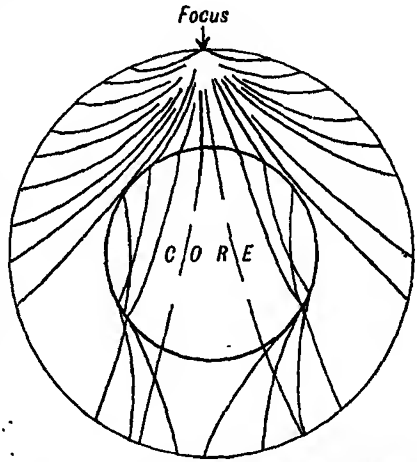


FIG. 3.—DISTANT EARTHQUAKE AS RECORDED ON SEISMOGRAPH.

ground. The motion of the beam-end actuates a needle which writes a continuous record on a rotating drum. The needle can record movements of the ground quite imperceptible by ordinary means; small vibrations, due to local traffic or other like disturbances, cause a continual oscillation or jogging of the curve. Among the more important systematic causes of shaking is the beat of breaking waves on the shore, whose effect is appreciable many miles inland. An earthquake shock, even though very distant, produces much larger disturbances in the curve.

The characteristic earthquake trace (Fig. 3) shows first a few small swings, the "first preliminary tremors," followed after an interval by the "second preliminary tremors," and finally by the much larger waves of the "main shock." The three sets of waves correspond with those mentioned above as possible in a solid. They represent, in the order named, the P waves, the S waves,

and the L waves. The L waves have followed a long circumferential path from the focus, but the P and S waves have followed shorter paths at greater depth within the body of the earth, and hence arrive first. In a homogeneous solid the seismic rays of P and S waves would be straight lines, but they are subject to reflection and refraction, like light rays, at the interfaces of two media differing sharply in density. A steady change of density will cause a curved path, and since, apart altogether from any sudden changes, density increases with depth in the outer regions of the earth-ball, the seismic rays, governed by laws kindred to those of optics, will be concave towards the surface in this region (Fig. 4).



[*After Sieberg and Gutenberg.*

FIG. 4.—PATHS OF EARTHQUAKE WAVES THROUGH THE INTERIOR OF THE EARTH.

In recent years, careful examination of earthquake records has revealed further complications. The record of the shock in the Kulpa Valley in Croatia (1909) showed two extra sets of waves, similar in properties to the P and S waves respectively, but with a slower rate of travel. They were distinguished as the P_g and S_g waves. Near the epicentre they alone were present, but further afield the P and S waves, as originally recognized, made their appearance; while, finally, at greater distances still, the P_g and S_g waves died out, leaving only the P and the S waves. The analysis of the record of the Tauern shock of 1923 revealed a third pair of waves of similar characters whose velocities proved to be intermediate between those of the P–S and P_g–S_g set. These have been distinguished as the P* and S* waves. It is particularly this recognition of the trebling of the earthquake record in respect of waves of longitudinal and transverse type which has led to notable results in the exploration of the outer layers of the earth. It may be noted that, in any case, the character of earthquake waves as recorded at distant stations would

strongly suggest some system of layers or shells. But the latest results permit us to go much further than this and obtain some idea of the constitution and thickness of the shells. Upon the discovery of the P_g and S_g waves it was quickly perceived that the facts could be explained by the assumption that these waves had travelled in an outer rock-shell, while the P and S waves had been refracted into a deeper layer in which they travelled faster, and had then been refracted back to the surface. The P^* and S^* waves in view of their intermediate velocity thus indicate an intermediate layer. We arrive, then, at the conception of three rock-shells, the upper, intermediate and lower layers, the differences between the three sets of waves being attributed to their having travelled one in each of these different layers. Now the velocity of a wave gives a measure of the density and compressibility of the materials through which the wave passes. Since the velocities in the three sets differ not only as between the P and S constituent of each, but also as between the sets, important differences of density and compressibility clearly exist between the layers.[1] In attempting to identify the layers with known rock substances we are led naturally to compare the results of laboratory determinations upon rocks with the figures for density and compressibility as inferred from the wave velocities. The results are as follows :

The upper layer has properties closely comparable, though not identical, with those of granite, and it is now universally regarded as of granitic constitution. It must not be forgotten that considerable masses of sedimentary and metamorphic rocks, as well as igneous rocks denser than granite, are included in this outer shell ; so that some slight variation in the velocities from those proper to a pure granitic layer is not unaccountable.

The intermediate layer is undoubtedly kindred in composition to the rock basalt ; but some difference of opinion exists as to the state in which it exists. We must here recognize the important fact that a melted rock, with a definite chemical composition, may crystallize in different assemblages of minerals according to the physical con-

[1] The reader is warned against a confusion, natural on first reading, between the three varieties of waves P, S and L, physically distinct from one another, which proceed from each earthquake-focus and the three distinct sets of P and S waves, viz. P and S (ordinary, *i.e.* first discovered), P_g and S_g and P^* and S^*, which indicate a threefold layering in the materials transmitting the vibrations.

ditions, and particularly the pressure ; or, while solidifying in the ordinary sense, it may fail to crystallize at all, becoming a glass—a congealed liquid. This fact renders several views possible as to the nearest actual rock equivalent to the intermediate layer. Daly and Jeffreys favour basalt-glass (tachylite). Wagner, followed by Holmes, favours amphibolite [1] as the dominant constituent. Renewed and more accurate laboratory work upon these rocks will almost certainly indicate which more nearly fits the facts. Many writers are content to speak of the substance of the intermediate layer as basaltic ; it is, in any case, to be remembered that it is the source of the great eruptions of basalt which periodically flow out over the earth's surface.

The lower layer is certainly composed of rock material denser than basalt and rich, or potentially rich, in the mineral olivine. It is variously identified, in the scheme of surface rocks, with dunite or peridotite, but it is quite possible that the material is in a non-crystalline, glassy, state. Little is known as yet of the laboratory properties of glasses of this composition.

As regards the thickness of the layers, Jeffreys deduces 10–12 km. for the upper layer, his figures being derived from travel of earthquake waves beneath Europe. His figure for the intermediate layer is 20–25 km. Greater thicknesses for both these layers are favoured by German and Japanese seismologists. The upper layer has been assigned a thickness of as much as 50–60 km., but this is almost certainly excessive. Since the exact figures given are subject to revision, it is perhaps of more significance to point out that the upper layer cannot be of the same thickness everywhere, thickening notably under mountain tracts. For the lower layer, defined as dunite or peridotite, no explicit thicknesses are quoted, but it is probably much thicker than either of the others.

Before leaving the relatively more superficial regions of the earth-ball we must note one further point of great significance. The surface or L waves, which travel through the rocks of the continental crust and through those which form the floor of the oceans, show an appreciable difference in their rate of propagation as between the continental and oceanic portions of their route. Distinctly higher velocities rule for the oceanic tracts, notably

[1] An amphibolite is a rock of basaltic chemical composition, but consisting largely of the mineral hornblende.

the Pacific; whence it appears that the granite layer is there thin or absent. The velocities through the Atlantic floor are somewhat lower, and point to the probability that considerable masses of the granitic shell survive there.[1]

Finally, we may note that distant earthquake records throw light upon the nature of the central core of the earth. The velocities of both P and S waves increase with depth, to a depth of approximately three-tenths of the radius. We know, therefore, that to this depth the earth possesses the properties of an elastic solid. It was noted by Oldham in 1906 that at distances of 120° or more from the epicentre the S waves are lost, and since such transverse waves cannot be transmitted by fluids, the facts appear to indicate a core extending to approximately half the radius and possessing the properties of a fluid. More recent investigations have added some details, but the main conclusion remains unaffected. It has been shown that true P and S waves are not normally received at distances of more than about 104° from the epicentre, but that near its antipodes (the anticentre) a P wave, transmitted through the core, can be recognized, though no S wave is traceable. Apart from its action in failing to transmit S waves, the core produces interesting effects. On entering the core the P waves travel with reduced velocity and are hence refracted downwards, as shown in Fig. 4. The core thus acts as a lens, tending to bring the waves to a focus on the far side, while nearer the epicentre there is a species of earthquake-shadow, a region away from which the rays are refracted by the core.

We see, then, that the study of seismology, by leading to the discovery of discontinuities, or "anomaly planes," within the earth, has made it possible to reconstruct an outline picture of a core and concentric shells. It is quite certain that our knowledge of these matters will be further greatly increased by earthquake study, possibly supplemented by the study of controlled artificial explosions which set up vibrations of the same type. Meanwhile we may glance at the problem presented by the nomenclature of the shells.

The *zoning of the earth's interior*.—Van der Gracht, following Gutenberg and others, has attempted a summary of existing knowledge in the following form:

[1] Recent results indicate the probability that appreciable amounts of sial occur also over the floors of the Indian and Pacific Oceans.

	Density	Thickness
Outer sial crust . .	2·75–2·9	60 km. (under continents)
Inner silicate mantle (in part = sima) .	3·1–4·75	1,140 km.
Zone of mixed metals and silicates . .	4·75–5	1,700 km.
Metallic nucleus . .	11	

This suggested scheme is illustrated in Fig. 5. It should be compared, so far as the outer shells are concerned, with the rather different arrangement deduced by Jeffreys, which we have noted above. The main discrepancy is in the thickness attributed to the sial. However, if we identify the "upper layer" with the sial, reducing the thickness of the latter accordingly, the "intermediate" and "lower" layers fall within the upper part of the inner silicate mantle and may reasonably be grouped as equivalent to the sima, wholly or in part. Such is undoubtedly their affinity in terms of composition, but if we have regard to physical state and mechanical function in the process of formation of terrestrial relief, it is probably better to follow Holmes and treat the upper and intermediate layers as the "crust" and the lower layer as the "substratum." The distinction in this case is one of thermal state and is explained in the sequel. It may be convenient to state the matter in schematic form thus :

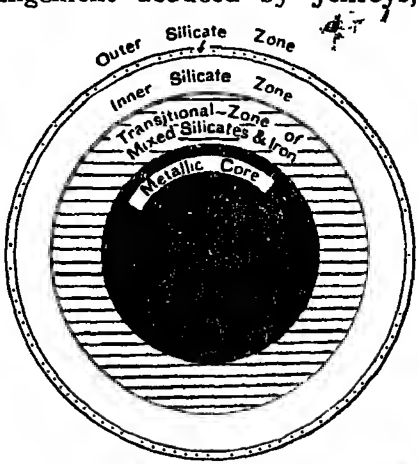


FIG. 5.—THE EARTH : CORE AND OUTER ZONES.

$$\begin{array}{lll} \text{Sial—Upper layer} & \multirow{2}{*}{\}\ \text{Crust}} \\ \text{Sima—}\left\{\begin{array}{l}\text{Intermediate layer}\\ \text{Lower layer}\end{array}\right. & \\ & \text{Substratum} \end{array}$$

Though the distinction between crust and substratum is of high significance, the terms sial and sima are generally

useful in many discussions, and we may perhaps claim for them a temporary reprieve on this ground.

The thermal state of the interior.—The steady increase of temperature with depth, at an average rate of about 1° C. per 32 metres, implies a flow of heat from the interior of the earth to its surface, where the heat is lost by radiation into space. The amount of heat thus lost is calculable if we know the underground temperature gradient, the average conductivity of the rocks of the crust, and the area of the earth's surface. If we know the amount of heat lost we are enabled to attack the problem of the date of the solidification of the crust and, also, that of the amount of radial contraction which must have resulted from the cooling. Among the earlier treatments of the problem was that of Kelvin, who supposed that the globe had solidified as a whole at a temperature of 7,000° F. and had subsequently cooled as a solid body. He was thus led to calculate that not more than 40 million years had elapsed since the earth assumed a solid exterior.[1] The whole of his calculations and the conclusions drawn from them were, however, invalidated by failure to take into account the then undiscovered radio-active elements, the spontaneous disintegration of which liberates large quantities of heat within the earth.

The two chief radio-active elements are uranium and thorium. Both are widely distributed through rocks as constituents of certain minerals. They undergo atomic disintegration spontaneously and continuously, the process being quite unaffected by such temperatures and pressures as exist even in the central parts of the earth. The end products of the disintegration are helium and lead ; but a number of intermediate products have been recognized, of which the best known is radium.

Two aspects of the radio-active process are of vital importance to an understanding of terrestrial history and surface forms. On the one hand, though the discovery of radio-activity completely transformed the older problem of the " age " and cooling history of the earth, the same line of research afforded a direct and delicate means of estimating geological time. The end products of disintegration, helium and lead, have gradually been accumulating at known rates in radio-active minerals since these minerals were first formed. Assuming that

[1] This was his final verdict of 1897: his earlier calculations indicated somewhat more extended periods.

no lead was originally present in the mineral, the ratio of the amounts of uranium and lead becomes a definite measure of the age of the mineral and of the igneous rock in which it crystallized. The fascinating applications of this important idea pertain to the field of geology and must not detain us here. It must suffice to note that the age of the oldest known igneous rocks is approximately 1,500 million years, so that the "age of the earth," reckoned from actual birth, must exceed even this high figure. The approximate age in years, as deduced from uranium–lead ratios, of some of the recognized periods of the geological past is indicated in Fig. 6. What is of more importance to our present considerations is that it is now possible to reverse Kelvin's problems, and taking the age of the earth as known, to deduce its thermal history and present state, instead of deducing the age from an assumed thermal history.

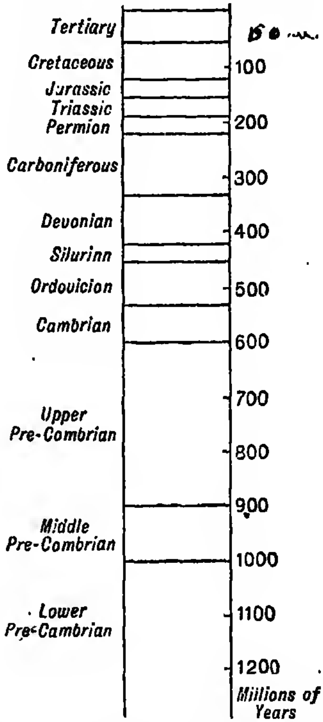


FIG. 6.—GEOLOGICAL TIME. Radio-active dating of the chief geological periods.

The second aspect of radio-active disintegration in the crust concerns the actual heat set free in the process, an absolutely vital factor in the evolution of the earth. As Holmes has remarked, to ignore it "would be as wrong as to ignore the effects of gravitation." In assessing the heat output of radio-activity we must take note of the fact that though the elements uranium and thorium are much more strongly radio-active than all others, rubidium and potassium also show the same properties in feebler form. Though rubidium is so rare that its heat output can be ignored, potassium exists in enormous quantities in the rocks of the crust, notably in certain felspars and micas; and though its heat output per gram is only about 1/3000 of that of a gram of uranium, this is largely compensated by its

overwhelming preponderance in amount. In fact, it contributes appreciable quantities to the total of radio-active heat with which we have to reckon.

If the distribution of radio-active elements in depth were the same as that revealed by analysis in surface rocks, the amount of heat developed within the earth would be many times the amount lost by conduction to the surface. The dilemma thus presented has evoked a number of suggested solutions. Some writers have supposed that the earth must actually be getting hotter, but this view is out of harmony with the facts, and quite unacceptable. More reasonable is the view that the radio-active substances are appreciably concentrated in the more superficial layers. For this there is a certain amount of experimental warrant, for rocks of the granitic or sial type show a much higher radio-active content than those which are believed to form the heavier under-layer, and these, in turn, greatly exceed the iron-meteorites in respect of their content of heat-emitting substance. It has, therefore, been deemed probable that the processes of primary separation of the iron core from the silicate shell, and of the two or more parts of the silicate shell from each other, have effected a natural upward concentration of the radio-active elements. By assuming certain definite distributions of radio-active matter in depth it is possible to "arrange" for the earth to cool, by making the internal heat output less than the heat loss at the surface. Any such assumption involves a much slower cooling process than was imagined by Kelvin. We shall see, however, that weighty objection has been made to the mathematical "arrangement" for the cooling of the earth; it is questioned whether the facts to hand render it reasonable, or even possible, to keep the estimated quantity of heat down to such a low figure.

Jeffreys, assuming a rapid decrease of radio-activity with depth, has given a quantitative account of the cooling of the earth. While the ball was still liquid, cooling would have proceeded by convection currents of heated material rising towards the surface, while return currents carried down the cooled surface liquid. During this phase the fall of temperature is likely to have been fairly uniform throughout. Eventually the temperature would fall to the solidification point (*i.e.* the melting point) in some layer. This would not be the surface layer, for the temperature of solidification is raised by pressure. It is,

therefore, reasonable to suppose that solidification would begin some way below the surface and extend upwards by degrees, thus forming a solid crust. Thereafter the mode of cooling would be quite different, viz. by conduction through the crust. Jeffreys calculates that 30 km. below the base of the "intermediate layer," cooling since solidification must have amounted to about 800° C.; but at 600 km. below this level he calculates that the cooling amounts to a few degrees only. This is an important conclusion, for it implies that at this depth and, perhaps, at even smaller depths, the material of the earth, though rigid in respect of the transmission of earthquake waves, must be "weak" and capable of flow under great pressures, *i.e.* it must possess some of the properties of a fluid, though in other respects it behaves like a solid. In a somewhat analogous way, a rod of cobbler's wax can be made to vibrate and to emit a musical note, while, left lying under the influence of its own weight, it will flow out flat. The distinction is one between "rigidity" and "strength," both terms being used with a strict technical meaning and *not* in their colloquial sense. In dealing with the materials of the earth, it may be regarded as highly probable that while "rigidity" becomes considerable as soon as the solidifying point is past, "strength" may remain exceedingly small, until some hundreds of degrees of further cooling have taken place. We are thus led to perceive the reality of a distinction between the lithosphere, in which the rocks are both rigid and strong, and what Barrell has termed the "asthenosphere" (sphere of weakness), where the materials are rigid, but lack strength.

It is not to be conceived that the junction between these is necessarily or probably sharp; a gradation of characters is obviously more likely. Nor can we assign on the basis of Jeffreys' calculations any definite thickness to the lithosphere which, according to his views, would include at least the "upper" and "intermediate" layers of seismologists and an unknown fraction of the "lower" layer.

As we have indicated above, the view of the earth's cooling history and present internal condition, so thoroughly worked out by Jeffreys, though it commands the fullest respect and attention, has been subject to some question. The difference of opinion concerns the distribution of radio-active matter in depth. It is agreed that if the radio-active elements were distributed uniformly, the mode of cooling of the earth would have been

quite different from that indicated by Jeffreys. The excess of heat would have left the interior fluid to within a comparatively short distance of the surface. There is not the slightest warrant for assuming a uniform distribution, but if the deeper layers are even slightly richer in radio-elements than Jeffreys has allowed, there would be an excess of heat tending to fluidity. Holmes has contended strongly against the assumption of too complete and unnatural a concentration of radio-activity towards the surface. He regards the upper and intermediate layers, *i.e.* the "crust" as defined by him, as competent to supply the heat lost at the surface, and points out that if the substratum possesses only 1/700 of the radio-active content of ordinary basalt, there is an available excess of heat which should suffice, in his view, to maintain a fluid condition and one permitting slow convection currents right up to the base of the crust. On this view the "crust" and the lithosphere become almost identical, while the asthenosphere includes all, or most, of the substratum. The possibility of convection currents at comparatively small depth has an important bearing on the problem of finding adequate forces for continental drift, mountain building, etc., and we shall return to the matter in the sequel. The whole theory, as sketched in outline by Holmes, awaits thorough mathematical investigation; but it certainly succeeds in indicating acceptable explanations of the major relief features of the earth.

Note.—The surface waves appearing in earthquake records were first identified with the waves described by Lord Rayleigh in 1887, in which the motion is wholly in the plane containing the vertical and the direction of propagation. A. E. H. Love showed subsequently that, in a solid with "layered" structure, it was possible to set up waves with a strong horizontal component at right angles to the direction of propagation, and the later analyses of earthquake records have shown that both Rayleigh and Lowe waves are present.

The latest work suggests the existence of P waves in *three* distinct intermediate layers, between the upper and lower layers, and the S waves corresponding to two of these are known.

CHAPTER III

THE THEORY OF ISOSTASY

Introductory.—A survey of the variations in the direction and intensity of the force of gravity and their distribution over the surface of the earth, has thrown much light upon the relation of its outer shells and the nature of its major relief forms. The theory of isostasy embraces a rather complex body of ideas bearing on these subjects, to which there are several approaches. The word "isostasy" was first used by the American geologist Dutton in 1889 to express his conception of a state of balance which he thought must exist between large upstanding areas of the earth's surface, mountain ranges and plateaux, and contiguous lowlands, etc. He suggested that they must be "compensated" by the existence of relatively light rock material beneath them, in order that the crust in such regions should remain in a state of mechanical stability on a rotating earth. The further development of the idea has been largely the work of geodesists and, in fact, the first relevant observations in this field were made before Dutton gave expression to his idea from the geological standpoint. We may therefore best view the subject from the geodetic angle in the first place.

Latitude measurements.—The aim of geodesy is to determine the shape and size of the sea-level surface of the earth. On a non-rotating sphere this would simply involve the determination of the astronomical latitude of two points on a meridian, and the measurement of the actual distance between them. We should then have a difference of latitude of x° equivalent to a distance of y miles, and the circumference of the earth could be obtained from the simple equation:

$$\frac{y}{\text{Circumference of earth}} = \frac{x^\circ}{360^\circ}$$

The fact that the earth is not a sphere but a spheroid, showing polar flattening, imports a slight complication, but, if this were all, observations of the latitudes and distances apart of three stations on a meridian would suffice to determine the shape and size of the earth.

Astronomical determinations of latitude are made with reference to the "vertical," *i.e.* the direction of a freely hanging plumb-bob, which shows the direction of the force of gravity at the station in question. If the earth were of spherical shape and were thus entirely covered by the oceans to a uniform depth, the plumb-line would everywhere set itself normally to the ocean surface. The actual conditions are much more complex. The considerable protruding masses of land, islands, mountains, and plateaux, exercise attractive forces which pull the plumb-line out of the true, or "deflect the vertical." The existence of this disturbing factor was realized in 1859 during the course of measurements on the Indo-Gangetic Plain. The difference of latitude between two stations as determined, on the one hand by astronomical methods and on the other by measurement (triangulation), was found to differ appreciably. Since one of the stations was less than 100 miles from the Himalayan mass it was clearly seen that the attraction of this vast block must result in deflecting the vertical. An attempt was therefore made by Pratt to estimate the amount of attraction and allow for it. He assumed that the mountain mass as a whole had a density approximately that of the average rocks of the surface crust, say 2·7, and his calculation showed that, on this basis, the mountains should cause a much larger deflection of the vertical than they actually did. So unexpected a result naturally challenged interpretation. As we shall see in the sequel, Airy proposed a simple explanation which has since found favour in many quarters. For the moment, however, we may be content with observing that two general alternative suppositions were available: either that the mountains had not their supposed density, but were exceptionally light, or that the excess of matter which they represented was, in some sense, compensated for by a deficiency of density beneath the surface, either locally or farther afield. Both possibilities were canvassed in ensuing years. The former took an extreme shape in the supposition that mountains were "bubbles," wholly or partially hollow, but this was so evidently at variance with simple geological fact and inference that the alternative view was inevitably preferred. Thus the conclusion reached was that local excess of attraction, due to major relief features, was compensated for by some deficiency of density below the surface.

Gravity measurements.—We may now pass on to review the parallel conclusions derived from a study of the variations of the intensity of gravity. On land it is measured by observing the number of vibrations of a pendulum in a given time. At sea practical difficulties arise in the use of the pendulum, since stable support cannot be given it on board ship ; but a certain amount of information can be got if the pressure of the atmosphere is determined simultaneously by the mercury barometer and by the boiling point thermometer. The first method gives a result which depends on the intensity of gravity, while the second is independent of gravity. The comparison of the two results thus affords a means of determining gravity. The method is rough, however, and latterly extensive use has been made, both on land and at sea, of the torsion-balance, a most delicate instrument in gravitational survey.

If the earth-spheroid were a homogeneous ball, simply showing polar flattening, the value of gravity would be the same for all points in the same latitude. Since in respect of gravitational attraction the earth's mass is to be regarded as concentrated at its centre and is so treated in calculation, the value of gravity would increase slightly from equator to pole as distance from the centre of the earth decreased. The value of gravity thus depends upon latitude. Further, on the earth as it exists, observing stations are at varying heights above sea-level, and thus at varying distances from the centre of attraction, so that gravity will depend upon elevation. Various formulæ have been devised to permit the calculation of the value of gravity at a station whose latitude and elevation are known. Values thus calculated are in fair agreement with observed values, but certain discrepancies still remain. Attempts have been made to reduce them by introducing longitude as a factor, since the earth is unevenly shaped in its equatorial cross-section, and distance from the centre thus varies slightly with longitude. No appreciable correction can be obtained in this way, however, and it is evident that some much more important factor must be sought.

On consideration it will be evident that, as with plumb-line observations, the topographic situation of the station must be taken into account, for the attraction of upstanding masses on all sides will in part control the motion of the pendulum. Accordingly, during a gravity-survey of the United States by the Coast and Geodetic Survey,

extensive computations were undertaken for each station to evaluate the attractive effect both of immediately surrounding masses and of the larger physiographic elements over a wider field. In considering such surface irregularities it must be assumed, as in Pratt's calculations, that the attracting bodies are of normal rock density. The calculated values of gravity "corrected for topography" in this way still show anomalies and hence, as with plumb-line experiments, we are forced to envisage possible variations of density below sea-level as disturbing causes. In general, the conclusion reached is the same, viz. that excess of superficial mass is compensated for by sub-surface deficiencies in density.

The concept of compensation.—The practical problem of bringing the observed and calculated values of gravity into agreement necessarily demands for its solution more than the general conclusion just noted. We need a precise indication of where and how sub-surface densities vary. Since the matter is beyond the range of direct observation the only course is to make various assumptions as to the distribution of density, base calculations upon each, and thus determine which assumption affords the best correction of calculated gravity values: *i.e.* causes the anomalies most clearly to disappear. The staff of the U.S. Coast and Geodetic Survey undertook this enormous task under the direction of Hayford, and latterly of Bowie. Hayford assumed that there was a level below the earth's surface, called by him the "level of compensation," below which densities were uniform throughout any given shell of the earth. Above this level the effective variations of density were presumed to exist, and for purposes of calculation a very simple assumption was adopted as to the nature of the variations: viz. that for contiguous "columns" of equal cross-section based upon the level of compensation the density was inversely proportional to the height. A diagram (Fig. 7) will render this conception clear. Here we have four imaginary columns reaching down to the level of compensation and underlying an interior plain, a plateau, a coastal plain and the adjacent off-shore area, respectively. The assumption is that the varying volume of matter in the several columns is compensated by their density, in such fashion that they exert equal downward pressure at the level of compensation and thus balance one another. The "equal-standing" concept contained in the word isostasy will

readily be appreciated in the light of such a picture. The same principle is illustrated in Fig. 8, where columns of equal cross-section cut from various metals and ores of different density are seen floating in mercury.

The application of this idea to the correction of gravity calculations clearly depends on the assumed depth of the level of compensation.

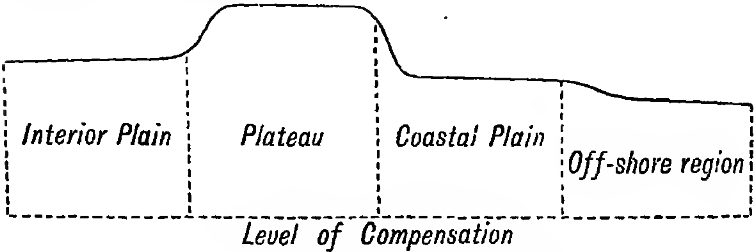
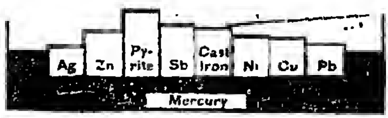


FIG. 7.—AN INTERPRETATION OF ISOSTASY.

It has been pointed out by mathematicians that, in theory, the number of postulated conditions which will satisfy the gravity requirements is infinite. We have, however, definite evidence that density variations do not extend beyond a limiting depth, for neighbouring stations are affected differently. If the cause of an irregularity were situated 1,000 miles below the surface, the effect would be sensibly uniform over an area of 300 square miles. This condition is not realized in practice; the causes we are seeking are certainly located in the outer crust. It is, in fact, vital to remember that although the treatment of the problem has been abstract and mathematical in form, it is feeling after physical realities, definite features of the earth-ball; and we are entitled to utilize the methods of direct observation and inference, so far as they will apply, in limiting the scope of the mathematical inquiry. Hayford concluded that a depth of the compensation level of rather more than 100 km. constituted the best simplifying assumption. By its means plumb-line observations can be consistently corrected, and the gravity anomalies generally reduced to about one-tenth of their former value. His figure refers to the United States; others have been suggested. In any case it would



[After Bowie.

FIG. 8.—AN EXAMPLE OF ISOSTASY.

be anticipated that each major region needs separate consideration in regard to the most convenient placing of the assumed compensation level.

After correction "for isostasy," on the lines indicated above, gravity values still show certain small "residual anomalies." These are believed to be due to the evident differences of density between contiguous rock masses, ranging from hardly consolidated sediments to dense crystalline rocks, in the immediate vicinity of the station; and in this connexion it is to be noted that recently there have been significant developments in geophysical prospecting, involving the use of detailed torsion-balance surveys for the location of ore-bodies, salt masses and oil-bearing rocks, whose density differs appreciably from that of surrounding materials.

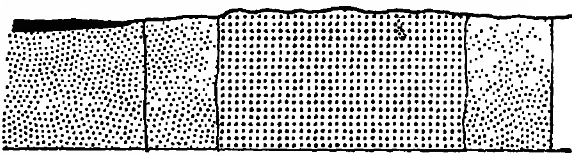
We may now pass on to consider those aspects of isostasy that most nearly concern the geographer and geologist. Our main problem is to inquire what physical meaning, in terms of structure and relief, is to be read into the concept of compensation. Though the geodesist may rest content with an assumption which facilitates calculation, it must clearly be brought into some relation with the findings of observation on earth structure. Fig. 7 illustrates a mathematical conception; it clearly must not be taken as a picture of structure. Already it is fair to claim that its use in literature and discussion has led to crude and erroneous ideas of earth-movement, etc. Let us consider, in the light of the column conception, the consequences of a disturbance of balance. If erosion removes material from an inland column and deposits it on the sea floor, the redistribution of mass should involve a rise in the denuded inland column and a corresponding depression of the loaded sea-area. To complete the idea it is necessary to envisage some sort of drag or flow of sub-crustal material towards the rising column at or below the level of compensation. That some such mechanism operates is indeed very likely; geologists have irrefutable evidence that sediments can depress the floor of a loaded area to a limited extent, and some species of sub-crustal flow has been invoked on many other grounds. But clearly we are not justified in regarding the crust as composed of lumns, moving up and down independently; such a c, iception flouts the facts of observation, and even if it st' l not, it would, on the geological side, create many more

problems than it solved. Moreover, the conception of rising and falling columns has led in the hands of geodesists to an over-emphasis of vertical movements at the expense of horizontal movements.

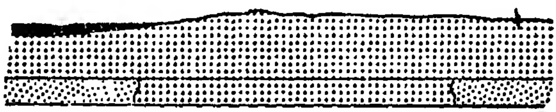
Their treatment of the matters at issue too often suggests that they are unfamiliar with the structure of the surface for whose foundations they are trying to account. From the standpoint of geology or geomorphology we can come to but one conclusion in regard to the column concept, viz. that in its simple form it is not in harmony with facts. The student should not dismiss it as simply "wrong"; it has served a most useful purpose and the faults in treatment which have developed are due rather to misunderstanding and misuse. We can now replace it by a more concrete conception, in harmony with the known facts of the structure of the earth and not less satisfactory to the geodesist.

We have reviewed in the previous chapter evidence which goes to show that considerable differences in density exist as between the major rock constituents of the earth's outer shell. The contrasted masses, however, are disposed not vertically (radially) in columns, but horizontally, as layers or shells. This fact must be reconciled with the isostatic conception. As long ago as 1859 Airy in commenting on Pratt's findings pointed out that the weight of mountains could not be borne by a rigid crust, but that support must be afforded by a great downward projection of their "roots" into a denser under-stratum. On this view the "positive attraction" of the upstanding mountain or plateau would be balanced by the "diminution of attraction" due to the replacement of dense "lava" by the mountain roots composed of specifically lighter material. Physically this is equivalent to saying that the mountain-mass is floating. Such a state of affairs would afford explanation of the plumb-line and pendulum observations, and is also in accord with many other considerations. It is now widely favoured as providing the real physical meaning of isostasy. We should not now call the under-stratum "lava," nor regard it as necessarily possessing the properties of a simple liquid, but the extension of Airy's idea, which regards the major relief elements, and, in fact, the continents themselves, as buoyed up or supported by a dense stratum of sima, must certainly be nearer the truth than the Hayford Bowie conception.

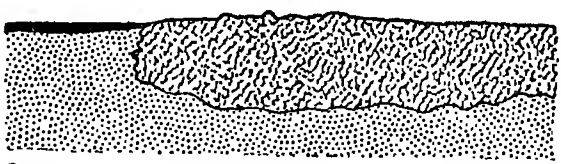
In 1925 Joly showed that the apparent conflict between the two ideas was not so radical as at first sight appears. He remarks that Hayford and Bowie, while rejecting the simple assumption of flotation by displacement in favour of a "structure more amenable to mathematical treatment," assume the fundamental law of flotation, viz. equal mass beneath equal areas. The origin of a continental crust in which density varies with surface-elevation above a level of compensation is regarded by him as "quite



a.



b.



c.

[*After Joly.*

FIG. 9.—INTERPRETATIONS OF ISOSTASY.

(*a*) Compensation uniformly distributed down to a certain plane. (*b*) Compensation restricted to a layer 10 miles thick. (*c*) The probable reality. In (*a*) and (*b*) light material in large dots, denser material in fine dots

unaccountable," and he further points out that, granted its origin, geological processes would quickly destroy so simple a condition. He calls attention to an alternative hypothetical distribution of density worked out by Hayford (Fig. 9) in which the effective density variations are confined to a layer 10 miles thick lying below a shell of uniform density. This is in close agreement with the flotation idea; the areas of low density in the 10-mile layer correspond with downward projections of the light

continental crust, while those of high density represent the intervening areas filled with the material of the heavier under-stratum (Fig. 9). It is, in fact, merely a simplified presentation of the irregular base of the continental shell and involves, not a single level of compensation, but rather a zone in which the compensating masses are distributed.

CHAPTER IV

THE NATURE AND ORIGIN OF THE EARTH'S MAJOR RELIEF

The permanency of the ocean basins.—The topographic features of the land areas of the globe are referable either to earth-movement, erosion or, in the commonest cases, to a combination of the two. Hills and valleys, plateaux and plains, normally bear the stamp of their origin upon them. The major features of the earth's relief, however, and particularly the primary division into continents and ocean basins, are clearly not the results of erosion, but reflect a deep-seated and, as we now realize, an early established ground-plan and cannot be regarded as other than tectonic—in the broad sense.

If we attempt to read any significance into the present distribution of land and sea it might forthwith be objected that existing conditions are special and temporary, coast-lines having shifted so markedly in the geological past and marine deposits being spread so widely over the lands, that the first general impression conveyed is of a ceaselessly changing geographic setting with few, if any, elements of permanence or plan. The older geologists did, indeed, conceive the ocean basins as relatively shallow troughs with ordinary sands, muds, etc., spread uniformly on their floors; and they found no difficulty in assuming the former inundation of continental interiors and the up-raising into land of the central deeper parts of the oceans. The progress of knowledge soon rendered this idea untenable; it came to be realized that ocean basins were far more permanent and fundamental earth-features than a superficial survey of the wide extent of marine sedimentary rocks would suggest. The facts which led to the advocacy of the "permanency of the ocean basins" were as follows:

1. Their form, as plotted from the soundings carried out in the latter part of the nineteenth century, was found to be wholly different from that formerly conceived. The cross-section of the broad abyssal trough, flanked by the rim-like continental shelves, might be likened to that of a soup-plate, rather than of a shallow evaporating dish. This form in itself suggested permanence; the

raising of a continent from the floor of the abyssal plain was a very different matter from a mere upwarping of a relatively shallow sea-bed.

2. The shallow-water sands and muds were found to be localized on the continental shelf and slope, while the abyssal plain was covered with distinctive "abyssal oozes." The sediments of the stratified systems extending over the land areas were found to resemble those of the continental shelves. With few exceptions truly abyssal deposits are unknown amongst the stratified rocks.[1]

3. Normal sedimentary rocks are rare on the oceanic islands, far removed from the influences of continental land.

In the light of these facts it became customary to regard oceans and continents as essentially permanent. Evidently shallow seas had spread over continental interiors, but the latter had never been depressed to abyssal depths; neither had the depths of the ocean ever formed continental land.

Explicit though these indications were, the progress of knowledge brought them into seeming opposition with biological facts. Biologists found it necessary to infer former land connexions across ocean basins to explain the distribution of land animals. It is, for instance, a familiar fact that the marsupial characterizes Australia; the only other living marsupial occurs in Chile, though fossil forms have been found elsewhere in South America; they are completely absent in the northern hemisphere. Similarly, the blind-snakes and certain butterflies are confined to the southern continents; and the same peculiar distribution characterizes the famous Glossopteris flora which is associated with the coal-bearing beds of the southern hemisphere and India. To explain these facts of distribution "land-bridges" were supposed to have existed, the now missing portions being supposed to have foundered at a later date. There was, then, a seeming complete impasse as between the geological and biological evidences. The salient factor, which may be said to have decided the issue, was the realization that the foundering of land-bridges was almost a physical impossibility, or at least

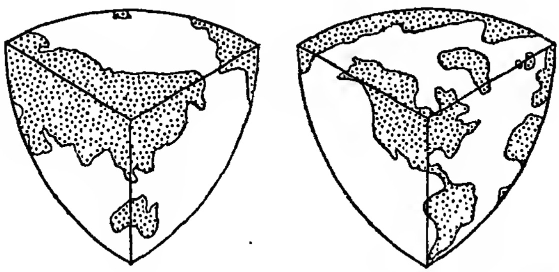
[1] Certain rock types have been regarded in the past by geologists as of abyssal origin, notably the "radiolarian cherts" of the Palæozoic systems and the Cretaceous chalk. Modern work has shown, however, that both these rock types originated in water of only moderate depth, and that neither is in any sense abyssal.

that it demanded very special and peculiar conditions. We have already reviewed the evidence for a density stratification of the earth's materials. There can be no question that the oceans are floored by material specifically denser than that which forms the continents. This renders it extremely improbable " that there could be such a shifting of materials in the depths of the earth's crust as would cause the sub-oceanic heaviness to give place to the sub-continental lightness." It also makes clear the difficulty of conceiving conditions under which the lighter material might founder. Some element of permanence of the continental masses is mechanically implicit in their physical constitution. This does not, however, imply literal permanence in geographical position, as the sequel will show.

The origin of the continents and ocean basins.—It being granted that the continents and ocean basins are fundamental relief features it is natural to inquire into their possible origin. The view adopted must depend, partly, on the manner of origin assigned to the earth. Kelvin hazarded the speculation that the continents might have been foreshadowed as nuclear clots, even before the gaseous phase of the earth's evolution had passed. Sollas suggested that the primary distribution of the hollows and bulges of the lithosphere reflected an original distribution of atmospheric pressure, the surface of the molten globe having been depressed in anticyclonic areas. The authors of the planetesimal hypothesis have sought to explain the earth's initial relief as due to the unequal infall of the planetesimal material. All these views imply that there is little order or underlying plan in the distribution of land and sea.

An attractive hypothesis which has enjoyed a considerable vogue was initiated by Lowthian Green in 1875. He claimed to see a rough tetrahedral arrangement in the distribution of land and water, such that the earth might be likened to a tetrahedron standing on one point (Fig. 10). In this attitude the four flat faces would represent the oceans, the Arctic Ocean corresponding with the upper, horizontal face; the horizontal edges with the land girdle round the Arctic Basin; the three vertical edges with the north–south land masses (Europe being conceived as separated from Asia, as indeed it has been in the recent past); the lower point with the Antarctic continent. J. W. Gregory has re-presented the hypothesis

in recent years, stressing the several well-known geographic homologies which support the theory, viz. the excess of land in the northern hemisphere ; the triangular shape of the major geographical units, the land units tapering southwards, the ocean units tapering northwards ; the general tri-radiate disposition of the land-masses in relation to the poles ; and the antipodal position of land and sea. All these may plausibly be regarded as consequences of a tendency to tetrahedral form. The theory, moreover, has an apparent basis in the fact that the sphere, the body with the smallest surface in proportion to its volume, tends to collapse into a tetrahedron, which has the largest surface in proportion to its volume. Thus the " tetrahedral hypothesis " was consonant with the familiar



[*After Griffith Taylor.*

FIG. 10.—THE TETRAHEDRAL EARTH.

views formerly current, which represented the earth as a cooling and shrinking globe, burdened with an excess of cooled crust which had to be accommodated to a dwindling nucleus. Unfortunately, there is one vital point on which the tetrahedral theory breaks down ; a tetrahedral deformation does not correspond with a figure of equilibrium and were such deformation to start, it would bring into being forces which, after a short time, would restore the spherical state.

Many other suggestions as to the origin of the continents have been made and we may briefly glance at some of them. Lapworth, emphasizing the dominance of the fold, or arch, in terrestrial morphology, regarded the continents and the oceans as manifesting the folding principle on a large scale. On this view the North American Continent would be a broad composite arch of the lithosphere, comprising two marginal " ge-anticlines " with a vast median sag representing the central plains. The Atlantic Ocean

would be the exact converse—a vast downfold, with marginally situated synclinal deeps and a central anticlinal rise (the Dolphin–Challenger Ridge). There is, as a fact, no evidence that the continents and ocean basins are folds, even in the widest sense of the term; were they so constituted there would be enormous mechanical difficulties in explaining their formation, and Lapworth's hypothesis must be rejected as out of harmony with our present knowledge. Lapworth's hypothesis was revived in a more precise and quantitative guise by Love in 1907. He sought to show, by mathematical analysis, that the earth-body, whose centre of gravity is not coincident with its centre of form, must inevitably undergo a series of harmonic deformations resulting in bold upwarpings and depressions which would form the ground-plan of its major

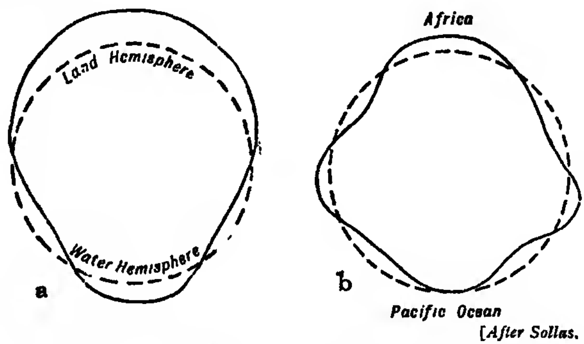


FIG. 11.—JEANS–SOLLAS' HYPOTHESIS OF EARTH DEFORMATION.

geographical features. The deduced configuration certainly bears a rather striking resemblance to the continental pattern; but it is very difficult to reconcile the supposed *modus operandi* with present geophysical conceptions, as the sequel will show.

Another hypothesis, which made an encouraging start in the early years of the present century, was based on the work of Jeans. From his study of the rotational stability of planetary bodies, it appeared that the earth, after giving birth to the moon, might have consolidated while in the "pear-shaped" form, precedent to the formation of a second satellite. On such an earth, it is evident that there would be a land-hemisphere, an annular girdle of ocean corresponding to the neck of the pear, and possibly, a small island continent representing its stalk-end, antipodal to the land hemisphere (Fig. 11*a*). Granted an

earth initially so constructed, Jeans suggested that the two hemispheres might crush together under their mutual attraction during cooling, expelling matter in their equatorial zone (Fig. 11*b*), and thus producing a bulging ring of land. Sollas endeavoured to show that the existing distribution of land and water showed some considerable measure of harmony with this theoretical scheme. Thus Africa was taken as lying centrally in the land hemisphere, with the Pacific hemisphere as its antipodes. No Pacific island representing the stalked end of the pear exists; but Sollas referred to certain evidence pointing to its former existence. The discontinuous ring of land (the Americas, Antarctica, Australia, East Indies, Asia, etc.), which separates the basin of the Pacific from those of the Atlantic and Indian Oceans, was regarded as possibly marking Jean's bulging ring (Fig. 11), the Atlantic and Indian Oceans being regarded as inbreaks in the land hemisphere, a supposition according with the discordant, transgressive or "Atlantic" character of their coast-lines (p. 352).

In connexion with the speculations of Jeans and Sollas it is appropriate to mention Osmond Fisher's suggestion that the Pacific Basin represents the scar in the lithosphere, consequent on the separation of the moon from its primary. This idea had the merit of explaining the earth's major asymmetry, and it provided some basis for explaining the difference between the Atlantic and Pacific types of coastline. It gains a new significance in the light of modern geophysical ideas (p. 40).

Two fundamental physiographic levels.—We have made somewhat extended mention of these several theories of terrestrial morphology in order to illustrate the fluidity of opinion formerly existing, and the limitations of the deductive method as applied to geophysical problems. As is so frequently the case, inductive reasoning, based on new facts rather than abstractions, has been invoked in recent years and has led to the fashioning of a new set of ideas, which, to an extent, constitute a break with tradition. While much remains to be learned it is fair to claim that we now understand something of the status and constitution of the continents; a new simplifying generalization is to hand.

The evidence for the existence of a density stratification of the earth's materials has already been summarized. There is converging evidence on many lines that the

oceans are underlain by material specifically heavier than the granitic material which underlies the continents, and is exposed on their surfaces wherever the thin pellicle of sedimentary material has been removed. With this fact in mind let us consider the generalized profile of the continents and ocean basins as revealed in the hypsometric curve. Sir John Murray's figures, expressing the areas falling within certain limits of height or depth over the surface of the earth, are as follows :

Land : Height in feet	*Area, millions of square miles*	*Percentage of whole globe*
Over 12,000 . . .	2	1
6,000–12,000 . . .	4	2
3,000–6,000 . . .	10	5
600–3,000 . . .	26	13
0–600 . . .	15	8
	57	29

Sea : Depth in feet	*Area, millions of square miles*	*Percentage of whole globe*
0–600 . . .	10	5
600–3,000 . . .	7	3
3,000–6,000 . . .	5	2
6,000–12,000 . . .	27	15
12,000–18,000 . . .	81	41
Over 18,000 . . .	10	5
	140	71

A curve drawn on a basis of these figures, plotting area against height, is shown on Fig. 12. It clearly represents

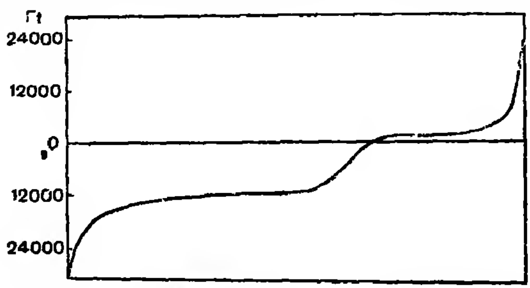


FIG. 12.—THE HYPSOMETRIC OR HYPSOGRAPHIC CURVE.

a generalized cross-profile of the continents and ocean basins and, resembling an ordinary section transverse to the continental edges, serves to eliminate all local and

varietal features. The salient facts brought out by the curve are :

1. The predominance of two levels representing, respectively, the general floor of the oceans and the general flat surface of the continents. The elevated regions of the continents and the depressed tracts, or "deeps," of the ocean have a quite insignificant aggregate area as compared with these wide tracts.

2. The steep continental slope—a dominant earth-feature which joins the two predominant levels. One is apt to get rather exaggerated ideas about the steepness of the continental slope owing to the exaggeration of the vertical scale in normal sections. Drawn to true scale it is by no means so conspicuous a declivity, but it is none the less a dominant earth feature.

These facts, and others considered later, make it clear that the continents are essentially rafts of the lighter sial shell, projecting above the general surface of the denser sima, which supports them and which underlies the floor of the oceans. Such a view is now almost universally current and may be accepted, in its broad aspect at least. There remain, however, certain related questions on which difference of opinion persists. We cannot here survey the whole of the wide field of speculation, but must content ourselves with giving a brief summary of the matters at issue.

Disposal of the excess of sial crust.—One problem which immediately arises is the discontinuous nature of the sial shell. To this fact, on the views here set forth, the continents owe their separate existence. It can, however, hardly be doubted that the sial, like the sima, was once continuous, for there is no known process which would lead to the concentration of the lighter part of the rock-shell in patches, during the separation from the metallic core.[1] We are, therefore, forced to choose between hypotheses which envisage, on the one hand, the gradual thickening of the sial at the expense of its superficial extent, or on the other hand the bodily removal of part of it. The former result could be achieved by no known process. As to the latter, it must be remembered that sinking of sial

[1] This statement may need qualification in the light of a suggestion due to G. F. S. Hills (*Geol. Mag.* 71, 1934). He envisages a condition in which active convection currents operated in the still unconsolidated "crust." Surface motions would thus be set up. away from the rising and towards the descending currents, and "scum" separating at the surface would be carried towards the latter.

blocks in the sima cannot be reconciled with the postulates of the flotation version of isostasy. Some writers, indeed, pursuing the line of thought suggested by the Hayford-Bowie theory of isostasy, have considered the possibility of large density changes in the rocks below the crust, leading to corresponding volume changes, and the bodily expansion or contraction of the crust. To such a view there are grave objections and its application to the problem of the vanished sial tracts creates more difficulties than it solves. The simplest, and most generally probable, suggestion is that the excess of sial crust has gone to form the moon. That the moon was formed by separation from the earth was a proposition generally conceded by astronomers and geophysicists during the last century, and though doubts have been expressed latterly, there remains considerable evidence in support of the idea. The exact cause of the separation, involving what is called "tidal resonance," need not concern us here. Any such separation must have taken place, according to Jeffreys, soon after the formation of the first solid crust. The loss of a large part of the sial shell may readily be imagined under those circumstances. Some confirmation comes from the fact that a globe the size of the moon would result from the rolling up of a layer 60 km. thick, spread over the oceanic areas of the earth. Such a layer would be thicker than the continental shell, but the density of the moon (3·46) is higher than that of average sial, and this may be readily explained, in part, by the inference—a very natural and probable one—that some portions of the heavier underlying shell were caught up in the separated mass. We may, therefore, reasonably assume that the missing portions of the sial shell have gone to form the moon. The student will be wise to regard this as hypothesis, certainly not as proven fact; but, unless or until insuperable objections are raised from the mathematical side, it will remain a readily comprehensible and very probable explanation of the facts; and one that, at least, harmonizes with the major geographical and relief features of the earth-ball.

Continental drift.—The late Professor A. Wegener first promulgated the idea of a horizontal motion or drift of the continents through the sima in 1912. A kindred suggestion had, however, been made by F. B. Taylor in 1910. Little notice was taken of the idea until 1922, when Wegener elaborated his thesis in a work entitled

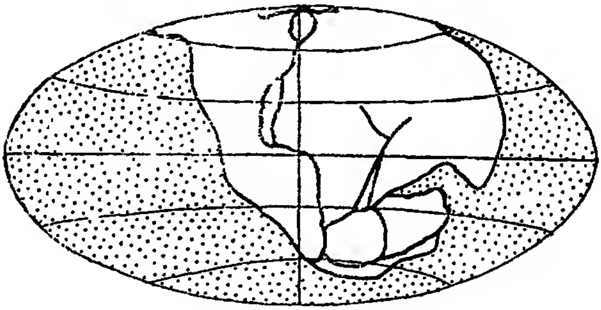
Die Entstehung der Kontinente und Ozeane, a revised edition of which appeared in English in 1924. Since then active controversy has taken place on all aspects of the questions at issue, and to-day a large literature exists.

In forming an estimate of Wegener's work it should be remembered that his hypothesis grew out of the need of explaining the major variations of climate in the past. There is clear geological evidence of climates resembling those of equatorial, tropical and arctic regions in latitudes far removed from lands where those climates prevail to-day. The solution to the enigma evidently involves the movement either of the lands or the climates. There must necessarily be severe limitations in theories of climatic change which involve suspension or alteration of the simple solar control of climatic zones, and though many theories have been proposed, involving changes in the composition of oceans and atmosphere and variation in the extent and elevation of land-masses and mountain ranges, few of them, in the opinion of meteorologists, are adequate to explain the larger climatic aberrations of the past. Wegener was primarily a meteorologist; and it is still true to say that much of the authoritative support for some form of continental drift comes from the meteorological side.

The evidence assembled by Wegener in favour of his theory covered a very wide field. He revived interest in the "jig-saw fit" of the opposed coastlines of the Atlantic, first noted long before, and he assembled a striking catalogue of resemblances in geological history and structure between the lands on its two sides. These resemblances included points of actual geological succession, of fossil faunas and floras, and of fold-lines or directions of geological grain. It is generally characteristic of the Atlantic coasts throughout, that the structure and relief lines are transverse to the coast. The most familiar example is afforded by the Appalachian mountain system whose frayed ends project into the sea on the North American side of the ocean and resume their course on the European side in the ancient folds of south-west Ireland, Wales, and Central Europe. If we admit that isostasy precludes the assumption that the linking tracts have foundered, a former *rapprochement* between the two sides inevitably suggests itself as an interpretation of the facts. Upon such considerations as these Wegener founded a general theory of continental drift. The

principal object of this theory was to reconcile the conflicting evidence relative to the distribution of past climates, and its initial inspiration was the apparent "jig-saw fit" of the opposed Atlantic coasts. Wegener supposed that the several continental masses were more closely aggregated in late Palæozoic times. Australia, Antarctica, Peninsular India, Africa, and South America formed a major southern block—equivalent to the Gondwanaland inferred by geologists on other grounds, while North America, Europe, and Asia formed a northern block, separated from the first by a wide belt of sea (the "Tethys," see p. 76).

Despite this considerable break of continuity the two great land masses formed essentially *one* major unit—named by Wegener "Pangæa" (Fig. 13). Portions of the



[*After Wegener.*

FIG. 13.—"PANGÆA."

continental mass were at this and other dates regarded as submerged beneath shallow epicontinental seas. Wegener further supposed that the South Pole was then situated in the vicinity of the South African coast; the possibility of considerable shifts in the position of the geographical poles is a definite element in Wegener's theory. The existing distribution of continental land was regarded by Wegener as having been achieved by the breaking up and drifting apart of the several elements of Pangæa. The forces invoked by Wegener to produce the drift were "differential gravitational forces," acting upon the protruding blocks of sial. One of these forces was believed to have caused a drift towards the equator while the other was responsible for a general westward drift. Thus, it was conceived that the African and European land blocks moved together under the influence

of the former force; while the Americas drifted westwards in response to the latter. The theory thus offered a mechanism of mountain-building. The Alpine ranges were regarded as "nipped" between the approaching jaws of Africa and Europe (p. 80), while the great western cordillera of the Americas was explained as the crumpling of the frontal edge of a drifting block against the rocks of the sea-floor. It should be noted that Wegener worked out a definite geological chronology for the supposed continental movements and the associated shifting of poles and equator. The main partition of the southern parts of Pangæa was achieved, in his view, during Mesozoic times, while further north the main movements were Tertiary in age. In collaboration with Köppen he traced the successive positions of the equator and the poles from Carboniferous times onward, by reference to the distribution of glacial, arid, and humid conditions. The great Carboniferous forests, of which the relics in the form of beds of coal now span the northern hemisphere in middle latitudes, were identified with the equatorial belt of that time.

Discussion of the Theory

Though the first publication of Wegener's theory passed almost unnoticed in the stress of the Great War, the dawning realization of its implications in the years following the war evoked a flood of criticism, rising not infrequently to the pitch of objurgation. The theory departs widely from the orthodox geological ideas of the nineteenth century, and it was perhaps inevitable, though unfortunate, that workers with a personal "stake" in such ideas should not only criticize the new doctrine, but actively resent it. Wegener abandoned completely the time-honoured "thermal contraction theory" of mountain-building (p. 120), and accepted fully the postulates of isostasy then still suspect in many quarters. The reconstructions of past geographies, if accepted, made nonsense of much that had been written on the subject from the older standpoints and, incidentally, withdrew emphasis from *vertical* movement in modifying world-geography—a hypothesis to which many writers had been greatly addicted. The brief foregoing summary of his views will at least make it clear that he presented a wide front to attack. His mistake, if mistake it was, lay in

his attempt to digest and summarize vast bodies of evidence, cognate to the new theory, but leading beyond the field of his own special competence. In the attempt thus to present a completely rounded theory he inevitably made many mistakes. It is now widely agreed that he handled his case as an advocate rather than as an impartial scientific observer, appearing to ignore evidence unfavourable to his ideas and to distort other evidence into harmony with the theory. As a result, it is fairly certain that no authority to-day would accept Wegener's theories in the original form. This does not end the matter, however; the general idea of continental drift does not necessarily stand or fall by Wegener's version of it. The central conception is immune from many of the criticisms valid in regard to points of detail. A review of the more recent literature of the subject reveals, broadly speaking, two classes of contribution. On the one hand, many writers have confined themselves to criticizing errors in Wegener's original synthesis. This is useful and necessary work, though some have been too eager to score mere dialectical points and to unearth discrepancies on points of detail. Other writers have sought to modify, extend, and correct the original theory, while retaining its cardinal conception.

Some of the chief objections to the theory, and possible answers to them, may be briefly considered here. In the first place it has been rightly contended that no force adequate to produce continental drift has been indicated. The tidal force invoked by Wegener to account for the supposed westerly drift of the continents would need to be 10,000 million times as powerful as it is at present to produce the required effects, and, if it had such a value, it would stop the earth's rotation completely in a year.

The equatorward force mentioned by Wegener is also quite inadequate to produce appreciable movement, given the present relatively high viscosity of the "sub-stratum." In an earlier day, when this viscosity was less, the force may have operated, but, if so, it should have concentrated the continental masses near the equator. Holmes has very reasonably argued that the fact that they are not so concentrated shows that some other force has been at work. We cannot claim to have recognized the force with certainty, though suggestions made by Holmes point to a likely line of inquiry. Meanwhile, the essential question at issue is whether drift has occurred. If its reality could be demonstrated our present inability to explain it would

not really constitute a criticism of the theory. A cogent parallel has been drawn between the present position and that formerly existing in regard to folded mountain ranges such as the Alps. The structures portrayed by geologists in such regions were formerly dismissed as mechanically impossible. Now that virtual unanimity has been reached as to their existence we are little nearer to a complete understanding of the mechanics of their origin—but this evidently does not prove that they are impossible.

Another difficulty frequently voiced is the seeming paradox involved in the assumption of sial masses drifting through the sima which, at the same time, is supposed to have sufficient strength to buckle their advancing edge. Here there is danger of confusion between the "rigidity" and the "strength" of a substance. "Strength" is the ability to resist permanent deformation under long-continued pressure, while "rigidity" is the "instantaneous resistance to distortion." Questions of "hardness" and "softness" are not at issue. It is possible to suppose that the sima is more rigid than the sial, but that the sial has greater strength. The respective properties of the two shells may perhaps be likened to those of pitch (cf. sima) and beeswax (cf. sial). It has been aptly pointed out that a rod of soft beeswax could be pressed into a mass of hard pitch, if the push were sufficiently slowly applied, and it might become buckled in the process. Further, it is not to be gainsaid, as a fact of geological observation, that basic rocks kindred in composition to the sima have frequently been induced to "flow"[1] by earth-pressures, while adjacent acid or sialic rocks have resisted such tendency. This may afford a clue as to what happens where a continental mass bears on the simatic floor of the ocean. It is further to be observed that frontal crumpling, as supposedly illustrated in the western cordillera of the Americas, involves not the folding of sial, but of weak sedimentary rocks, lying in a trough margined on both sides by sial. Wegener did not bring out this fact clearly, but it goes far to remove the difficulty here in question. Holmes is of opinion that along the frontal edge of a drifting mass, sedimentary rocks, caught between sialic jaws, may be raised into mountain ridges, while the floor of the ocean, composed of

[1] As, for instance, where basalts or dolerites are converted into hornblende schists.

rocks of entirely different physical properties, may be bent down to form "deeps."

Passing from geophysical to geological considerations, it has been quite fairly contended that the first and immediate attraction of Wegener's hypothesis undoubtedly lies in the "jig-saw fit" of the Atlantic coasts, but that the fit proves much less perfect upon inspection than at first sight. The reconstructions of Wegener and his followers (see *e.g.* Fig. 13) can only be achieved with the help of considerable distortion of the continental shapes.[1] Here, again, there are several opposing considerations to be urged. It may be conceded that the "jig-saw" argument has been over-stressed and that it possesses an undesirably plausible quality in popular demonstration. Nevertheless, certain significant lines of fitting survive the best efforts of the critic. Leaving aside the much-discussed fit between Africa and South America, which is much less perfect than at first appears, let the reader examine on a globe the outlines of Western Greenland, Baffin Land, Ellesmere Land (Grinnell Land), and the intervening marine channels. Here, at least, is a convincing piece of "fitting." But the real reply to this objection must take different ground. Whether or not Wegener was justified in introducing unexplained distortions into his reconstructions, it is patent from what we know of the crust that rifting and drift could not take place without such distortion. Granting the truth of the hypothesis, the continental outlines are much as we should expect to find them. A perfect "jig-saw fit" would, indeed, be an embarrassing feature to explain. A good debating point, but nothing more, has been made by those who point out that, granted the "jig-saw" method, Australia and New Guinea can be conveniently fitted into the Arabian Sea. Neither Wegener nor any other writer has, in fact, proposed such a fitting, for which there is not the slightest geological warrant.

In the same category we may group the objection that the "geological fit" of the opposed sides of the Atlantic is not as perfect as Wegener suggested. Those concerned to urge this view, notably Schuchert, do not deny a broad "parallelism" in the stratigraphical and structural features of the two sides of the ocean; such a parallelism

[1] Experiments with paper or plasticine outlines on a globe will quickly convince the reader of this.

has long been recognized. They claim that the relationship is that of broad similarity, rather than identity, and that it is explicable without recourse to large-scale drift. We shall return to the point below, and it is sufficient here to note that, whether or not Wegener overstressed the resemblances, we have no right to expect close identity of features, since a considerable and variable zone of sial may well have disappeared by thinning and submergence in the course of any rifting. The Central Atlantic rise (Dolphin–Challenger Ridge) remains as a probable witness to such a lost sialic belt (p. 16).

Finally, we may note two objections commonly raised, relative to the date and the direction of the supposed drifting. It has been regarded as ground for comment and incredulity that Wegener's presentation pictured no effective drift before the end of Palæozoic times. Critics have asked : " What kept Pangæa together till the hour for rifting struck ? Why did the process not become operative until that date ? " Such questions again constitute a criticism of Wegener's presentation of his case, not of the general theory. It is fair to rejoin, " What chance exists of reconstructing the obscure earlier drifting movements or of securing agreement on their nature, until the later, more legible, parts of the process have commanded wide assent ? " No present supporter of continental drift would seek to restrict its operation to post-Carboniferous time, though he might find it difficult to build up a convincing detailed picture of what happened before this time. There is little doubt that the continental nuclei were blocked out in pre-Cambrian times and, granted the possibility of continental drift, many features of Palæozoic geography point to its operation. Van der Gracht has suggested that an early Atlantic rift may be represented by the Lower Palæozoic sea which linked Europe and America, and that such rift may have been closed again by the approach of the two sides, giving rise to the Caledonian mountain-building (p. 49, 49).

Such considerations lead on directly to the objections concerned with the direction of drift. Here again the believers in continental drift must decline to be limited by Wegener's original suggestion. There are numberless difficulties involved in the assumption of a simple westward and equatorial drift. F. B. Taylor, who anticipated Wegener in enunciating the drift concept, deduced an outward radial movement from the two poles. Thus,

in the northern hemisphere, he traces a ring of mountains marking, in his view, the outer limit of the drift and comprising the Alpine–Himalayan chains, the mountains and island arcs of East Asia, the western cordillera of North America, and the ranges of Honduras and the West Indies. Taylor and others have parted from Wegener in regarding the Central Atlantic rise as marking the scar of an original rift from which the continental edges have withdrawn in opposite directions. J. W. Evans found evidence of a general drift eastwards, southward, and westward from Africa, toward the centre of the Pacific. These suggestions may contain more truth than those originally urged by Wegener. If continental drift is to be retained as a working hypothesis it must be regarded as capable of operating under widely variable conditions of speed and direction.

It may appear that while Wegener presented a theory widely open to criticism his followers have so accommodated and diluted the doctrine as to protect themselves, rather unfairly, against detailed criticism. This is true in some measure, but the position has arisen for definite reasons. Wegener overstated the case; but many are unwilling to see the stimulating central idea lost sight of, in the course of skirmishing over details. They would desire the central concept to be retained as a working hypothesis and are willing to see it shaped and modified in harmony with developing knowledge. What claim can it now make for such a measure of recognition? In answering this question one is confronted with the difficulty that evidence in support of it must be drawn from the whole geographical and geological field. To attempt fully to defend it here would involve anticipating many later sections of which the bearing must be left for the reader to appreciate. Nevertheless, recent years have not failed to bring forth much telling evidence in favour of continental drift and some of this may be briefly noted. In the first place, it is significant that few critics of continental drift, in the accepted sense, are willing to deny the reality of considerable horizontal movements in the continental crust. We shall find such movements plainly implicit in modern ideas of mountain-building (p. 76) which demand horizontal translation or "crustal shortening" of hundreds of miles. If only the order of such figures be correct, veritable continental drift is plainly implied. Certainly the problem of mountain-building is

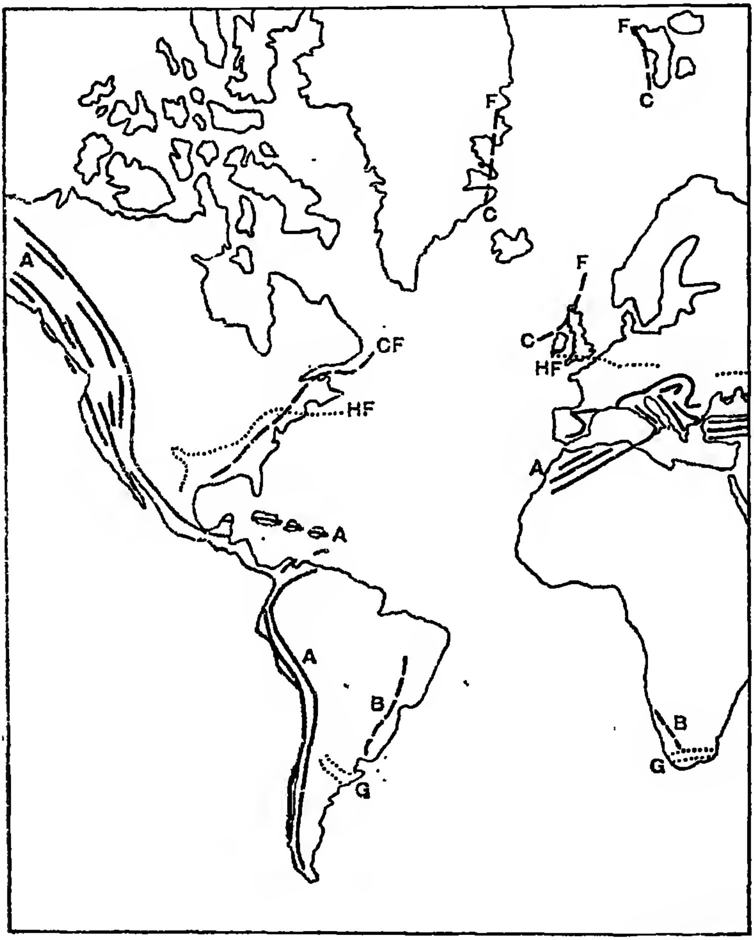
one in which the hypothesis of continental drift solves more difficulties than it creates. The same is unquestionably true in the field of palæoclimatology, and particularly in the case of the great Permo-Carboniferous glaciation at the end of Palæozoic times. No one questions the plain evidence that massive ice-sheets equal to, or even exceeding, the Pleistocene ice-sheets in dimensions were present more or less simultaneously at this time in India, South Africa, South America (Brazil), Antarctica, and Australia. A glaciation, extending over such vast areas, and athwart the present tropics, presents an almost insoluble enigma if one attempts to explain it on normal climatological lines. Such attempts have indeed been made, notably by C. E. P. Brooks, but they involve assumptions quite as difficult to concede as any made by the continental drift theory. A reconstruction of world-geography on the lines of that attempted by Wegener affords the only ready, though not necessarily the only possible, interpretation of the facts.

Lastly, it may be noted that geological correlation of the sides of the supposed "Atlantic rift" has made considerable progress since Wegener wrote. E. B. Bailey has pointed out significant analogies, too striking to be lightly dismissed as coincidental, between the arrangements of the Palæozoic mountain systems in Europe and America. We here anticipate somewhat the substance of Chapter VI, but Fig. 14 may serve to make the main facts clear.

The Caledonian mountain-folds of Northern Britain converge westwards towards the line of the later Hercynian folds. In South Wales and South Ireland the two systems meet and, as it were, begin to cross one another. As Bailey has shown, the crossing is completed in Pennsylvania; beyond which region the Hercynian is north of the Caledonian line. Equally striking is the fact that the Caledonian front (*i.e.* the north-western margin of the belt of Caledonian folds), present in Scotland and recognizable also in Western Spitzbergen, is not present in Norway. On the older hypothesis of continental foundering, it would have been presumed that the "missing link" lay submerged off the Norwegian coast. It proves, in fact, to be present in Eastern Greenland (Fig. 14).

For the South Atlantic coasts du Toit has made a detailed comparative study which brings to light comparable features. Thus the early Palæozoic mountain-folds known as the Brazilides, which trend roughly from north to south

from Brazil to the coast of Uruguay, appear to be resumed on the South African coast near latitude 27° S., and are traceable thence in a S.S.E. direction until they meet the



[*After Holmes.*

FIG. 14.—THE ATLANTIC RIFT AND ITS BORDERING MOUNTAIN FOLDS. CF, Caledonian front; HF, Hercynian front; A, Alpine folds; B, Brazilides; G, Gondwanides.

" Cape folds," almost at right angles, in the southern part of Cape Province (Fig. 14). The latter correspond with the mountain-folds known as the Gondwanides in South America. It is evident that the Gondwanides

and the Brazilides are shaping for a crossing just off the South American coast. Such crossing is actually achieved in South Africa. These facts must be considered, together with a host of further parallels adduced by du Toit between the geology of South America and South Africa. Similarities extending in some cases to most significant details are found in the structures, lithological character and fossil contents of the sedimentary rocks, and the character of the igneous rocks and the associated mineral occurrences. Such correlations demonstrate that opposing regions on the South Atlantic coast formerly lay within the same geological province; they do not prove former immediate juxtaposition of the regions in question; du Toit concludes that a strip of continental material from 200 to 500 miles wide has "disappeared" by thinning and submergence in the course of the rifting process, and such a conclusion is wholly in harmony with seismological evidence pointing to the existence of considerable surviving masses of sial on the Atlantic floor.

It can hardly be doubted that there is enough evidence now to hand to warrant our retaining continental drift as a working hypothesis. Much further work remains to be done and no useful purpose is served by forgetting or minimizing the difficulties that the theory is bound to meet. Such difficulties, however, appear no more serious than those which confront any theory of continental foundering or other large vertical movements. Opinions may differ as to the scientific ethics of Wegener's "advocacy," but it is beyond question that he has started a train of scientific inquiry and discussion of which the end cannot yet be seen; and it is possible to maintain that he could have achieved the object in no better way. A cautious and limited statement, hedged around with qualifications and provisos, might have given less scope for criticism, but less also for valuable and stimulating discussion. One cannot review the literature of continental drift without the reflection that critical acumen is commoner than creative genius, or power of synthesis, in the world of science; and it is probable that the memory of Wegener may yet receive justice from the host of smaller men who have indefatigably knocked the less stable props from beneath his original momentous theory.

Thermal cycles and marine transgressions.—A further geophysical topic of great general interest and importance

is that of possible large vertical movements of the continents, owing to changes in the density of the sima.

The sedimentary rocks of the continents, chiefly the deposits of shallow seas, make it clear that the sial blocks, now broadly emergent above the ocean, have been subject to periodical wide inundations by the sea, known to geologists as marine transgressions. These transgressions have followed one another in a regular, or cyclical, manner. The more important episodes of flooding are evidenced practically all over the world, a fact implying great uniformity in the relative movement of land and sea. Each transgression has extended conditions generally comparable with those of the present continental shelves, over the low-lying parts of the ancient continents, leaving in many cases only relatively small tracts unsubmerged. The plains of the modern world are the sites of the epicontinental seas of the more recent past—seas comparable in their nature and relations with, *e.g.*, Hudson Bay, which is merely a landward continuation of the shelf-seas at present surrounding the North American Continent. Such large changes in the relative position of land and sea clearly involve either bodily subsidence and uplift of the continental rafts or world-wide changes in ocean level. The latter have been termed eustatic movements, and may result from changes in the capacity of the ocean basins or variation in the amount of ocean water. The waxing and waning of ice-sheets is an important cause of such variation (p. 411). However, all the known or likely causes of eustatic shifts of sea-level would give rise to relatively limited effects and can hardly be invoked to explain the larger episodes of continental submergence. In these, we are compelled to assume, larger-scale movements of the continent were concerned.

The theory which is most generally acceptable, in its broad features at least, is that recently put forward by Joly. His postulates include the acceptance of the flotation concept of isostasy and also the fact that the sima below the continents has an appreciable content of radio-active elements which generate heat during their disintegration. The continental layer is even richer in these elements and sufficient heat must be generated within it to make good much of the loss by radiation at the surface.[1] If such is the case there can be little or no

[1] Jeffreys estimates the heat supplied by radio-activity as more than four-fifths of the whole flow of heat from the earth's interior to the surface.

escape of the accumulating heat of the sima below the continents, and though the simatic region has, at present, effectively the rigidity of a solid, continued raising of the temperature must ultimately lead to melting. If the sima below the continents were to become wholly or largely liquid, its density would be appreciably decreased and the buoyancy of the continents would be reduced. Though still floating they would sink farther into the substratum, or, in other words, their " draught " would increase at the expense of their " free-board " ; and the oceans would extend over their less elevated parts. Such, in outline, is the cause of the periodic submersion of the continents as pictured by Joly.

The repetition of marine transgression clearly demands that the theory shall provide for the dissipation of the accumulated heat and the re-solidifying of the sima, with resulting uplift of the continents. Joly regards it as probable that the accumulated heat escapes gradually through the floors of the oceans and thus permits a return to the *status quo*. His calculations, based upon our present knowledge of the radio-activity, conductivity, and melting points of rocks, lead him to suggest that transgressions have recurred in an interval of about 30 million years, a figure by no means widely at variance with conclusions drawn by other methods. The details of the theory have been severely criticized, particularly the suggested mechanism for dissipation of accumulated heat. Attempts have also been made to elaborate it and thus to remove some offending features. It should not be accepted as proved, but retained as an hypothesis which probably contains a large element of truth. It certainly succeeds in explaining the behaviour of the continental masses in a striking manner, and we may look to further investigation and discussion to shape it in detail. Plausibility is certainly not a criterion of truth in the sphere of geophysics and it is always necessary to insist upon rigorous quantitative tests of theory, but students of the earth have too often abandoned ideas unnecessarily, or adopted them unwisely, as the result of calculations too insecurely founded to deserve respect.

CHAPTER V

EARTH-MOVEMENTS AND GEOLOGICAL STRUCTURE

General.—Two sets of forces enter into the production of land forms. On the one hand we have external denuding agencies, grouped together by some writers as "exogenetic" and, on the other, internal uplifting, distorting or disrupting forces, which may be grouped as "endogenetic." The layman's view of landscape and the natural world generally is prone, too often, to invoke "upheavals" and "depressions" of a fantastic nature. Such a view was natural in ancient times before the potency of denudation was correctly appreciated. To-day it is clearly realized that exogenetic forces co-operate in all cases with the forces of upheaval and commonly surpass them in total effect. Nevertheless, in certain relatively limited areas, the work of endogenetic forces is directly traceable in relief features which, though modified by denudation, owe their salient character to earth-movement.

In these matters, as in others, the geographer is more concerned with results than with causes, but since genesis controls form and character in landscape, he must make some inquiry into the nature of the forces and movements involved. The subject of geological structure or "tectonics" is difficult and complex on the mechanical side, and one to which there are several approaches. We have available for study: (*a*) actual earth-movements now taking place at a measurable rate, or completed very recently; (*b*) the varying attitudes and relations of rock masses as exposed in the crust—the results of the operation of forces large and, generally, long-continued; (*c*) the results of experiments which seek to imitate geological structures.

Earth-movements of two distinct types are taking place within the range of our observation. Slow, or secular, movements of upheaval and depression are evidenced on many coastlines, while sudden movements, sometimes producing visible features at the earth's surface, are responsible for earthquakes. We may examine briefly the character of both these types of movement.

Secular upheaval and depression.—Apparent evidence of upheaval and subsidence in coastal areas needs careful consideration before it can be taken as proving movement of the land. Widespread and uniform change of level points to a movement of the sea rather than of the land. Any change in the volume of the ocean waters or in the capacity of the ocean basins must appear as a world-wide (eustatic) change of sea-level. Again, a change in the spheroidal form of the ocean-surface, due to change in the rate of the earth's rotation, would lead to submergence in some areas and emergence in others. In such circumstances the sea-level change would not be the same everywhere, but the amount of change would not vary rapidly from place to place. Actual movements of the land are generally more local in their effects, involving warping or bending. Subsidence may also occur as a result of the shrinkage of muddy or peaty deposits, through loss of water and compression. This naturally produces submergence, though no earth-movement in the accepted sense has taken place. Marine erosion of a coastline may also lead to results which simulate those of depression by warping.

When, however, all such cases have been allowed for and all doubtful and ambiguous evidence rejected, there remain well attested cases of local change of level which can be explained only by assuming warping of the crust. Rocks bored by marine organisms occur high above sea-level on the coast of Scandinavia and, widely, throughout the Pacific region, while reefs built by living species of corals occur in elevated situations in the West Indies and along the west coast of South America. Again, raised beaches, wave-cut platforms, sea-cliffs, and sea-caves occur frequently in coastal areas at elevations ranging up to hundreds of feet above the sea; in some cases these are referable to the effects of eustatic changes of sea-level, but elsewhere the beaches show obvious local tilting and warping, when traced over moderate distances. Further, a certain number of historical records exist which point to change of level. For example, the position of boat rings relative to sea-level has altered with the passage of time; it is estimated that the shores of the Gulf of Bothnia, near Stockholm, have been uplifted to the extent of 48 cm. during the last century; and many comparable and mutually consistent records come from adjacent regions in high latitudes: Spitzbergen, Novaya Zemlya,

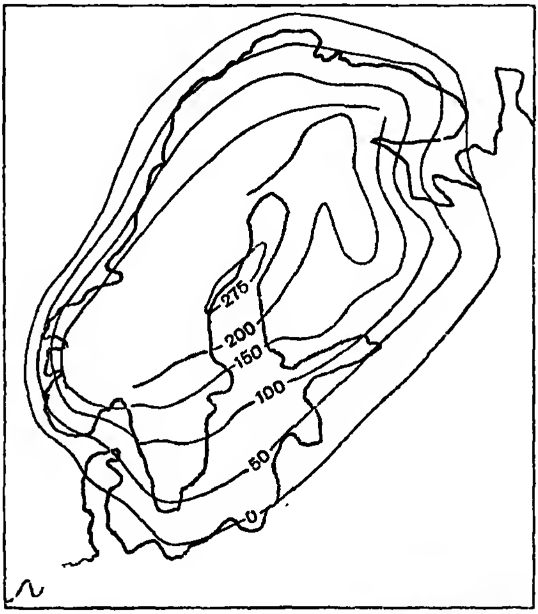
etc. In Scania, streets originally built above high-water mark are now below it, and there is evidence of the continuance of movement for considerable periods. It should be noted that evidence of uplift stands more chance of survival and recognition than that of depression, since the latter is commonly hidden by the sea, even where not destroyed by marine erosion. Nevertheless, the existence of "submerged forests," stumps of trees still rooted in soil and visible only during exceptionally low tides, has been widely noted. It has been abundantly proved that the southern portion of the North Sea was a low-lying forested area in the recent past and fragments of its peaty soil ("moor-log") are still recovered in dredging in the region of the Dogger Bank (cf. Fig. 269). It is probable, however, that the British submerged forests point to a eustatic rise of sea-level rather than a depression of the land, and this also explains many cases of irregular coastlines caused by the drowning of valleys, often adduced as evidence of earth-movement.

In a number of cases these recent changes of level are to be attributed to special circumstances. Thus, in the classic case of the Temple of Serapis near Naples, where movements of both elevation and depression are indicated by marine borings on the pillars and other evidence, we are dealing with a region of volcanic activity in which local movements are to be expected.

The complex changes of level in the Scandinavian region are related to the formation and subsequent melting of the Pleistocene ice-sheet which was centred on this tract. It has been shown that the weight of the ice caused definite isostatic depression, greatest in the central tracts where the thickness was greatest. The estimated extent of the depression is shown by isobases, or lines of equal depression, in Fig. 15. During the melting of the ice-sheet a two-fold effect was in operation : (*a*) the isostatic recovery of the land, rising as the load disappeared ; and (*b*) the rise of sea-level directly due to the melting of the local ice-sheet and of others farther afield. The two tendencies were opposed in effect and dominated each other in turn. During the earlier stages of ice-retreat submergence held sway, but thereafter isostatic uplift gained upon it, culminating in the phase in which forests, since submerged, grew beyond the present North Sea and Baltic coastlines. Finally, there was a renewed movement of submergence, due, it is supposed, to ice-melting in some other area.

Throughout the period in question, the submergent tendency was, presumably, world-wide in its effect, but the uplift was localized in the regions of former ice-loading. It has proved possible to estimate the rate of isostatic uplift at a number of points. (See also pp. 415, 416.)

The raised beaches of Scotland record a closely similar story of recovery from ice-loading. The highest of the beaches, now about 100 feet above sea-level, marks the initial stage of submergence during ice-melting, but



[After Sederholm.

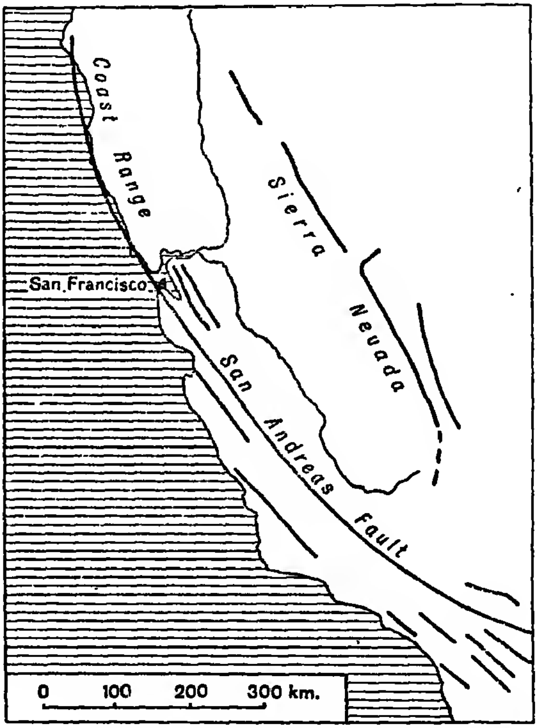
FIG. 15.—ISOBASES FOR SCANDINAVIA (IN METRES).

isostatic recovery raised the land thereafter and the next beach is at a level of 50 feet. An interesting confirmatory detail is the fact that this lower beach can be traced farther up the sea-lochs than the 100 feet beach, since the ice-tongues were shrinking up the glens in the intervening period and the water surface was thus extended.

The evidence for recent movements in the Pacific coast lands and in the East Indies appears to point to deformation, less local than that associated with volcanic forces or ice-loaded areas. As such, it is of more general significance

the actual fault cannot be identified, it is nearly always possible to show that the elongation of the isoseismal curves is parallel with the topographic and geological grain of the country.

The larger world-shaking shocks, such as occur in the Pacific border lands, present distinctive features of interest in that they frequently produce actual topographic features which indicate both vertical and horizontal movement.



[After Daly.

FIG. 17.—THE SAN ANDREAS FAULT.

The Californian earthquake of 1906, which wrought such havoc in San Francisco, presented many almost unique features in this respect. It was caused by a movement along the great San Andreas fault, which runs parallel with the American coastline for hundreds of miles, sometimes near the coast and sometimes a short distance off-shore (Fig. 17). The existence of the fault was known before 1906, though its full extent was not realized. Its course

lies, generally, in a topographic depression due, in part at least, to old displacements along the fault. Many small water-filled hollows and actual steps or fault-scarps mark the line of movement, the older scarps being partially obliterated by erosion, except in areas of low rainfall, where they remain sharp and clear. The movements of 1906 extended some of these scarps and caused new ones to form. The predominant movement was horizontal, fences, pipes, etc., crossing the fault being off-set to the extent of 20 feet. Vertical displacements up to 3 feet were measured in places. A trigonometrical survey conducted after the shock proved that both sides of the fault had moved, the western side northward and the eastern southward; and that the bending and displacement of the surface extended, with diminishing effect, to distances as much as 4 miles from the fault line. Visible displacements are traceable along the fault line for a distance of nearly 300 miles and the shock was sensible over a distance of over 700 miles in the direction of the fault, so that some subterranean movement must have occurred even where obvious surface signs are missing.

The suddenness and the violence of earthquakes, and the related appalling losses of human life and damage to property, tend to magnify their importance. It is well to remember that they are mere incidents in earth-movement and their greatest geological effects are soon obliterated by denudation.

Geological structures.—The evidence of earth-movements still in progress throws relatively little light on the major problems of the structure of the earth's crust. More is to be gained by studying the present attitude of rock-sheets laid down originally as sediments. Most of these rocks, of which the greater part of the continental surface is made, were accumulated in shallow water on or near the continental shelf; and their original attitude was sensibly flat or very gently inclined. Their present diverse positions imply movements brought about by forces. For clear thinking it is essential to keep the three ideas, structure, movement, force, distinct from one another. Existing structures make it clear that movements have taken place, yet though in a given case the nature of the movement may be quite evident, we may or may not be able to deduce the nature and direction of the forces which produced it. Even when the forces have been correctly deduced, there still remains the separate problem of the

origin of these forces. Structures, movements, direction and nature of forces and their origin thus constitute the elements of the tectonic problem. The geographer treats structures as more or less static features, being concerned primarily with their influence on form and on the distribution of water, oil and other economically valuable substances. He will, however, commonly find it helpful also to envisage the movements which have produced them, but he need not push his inquiry far into the question of forces, leaving this to the geologist and geophysicist. The treatment of structures in the following paragraphs is based upon these considerations, although the topic of forces is briefly discussed below.

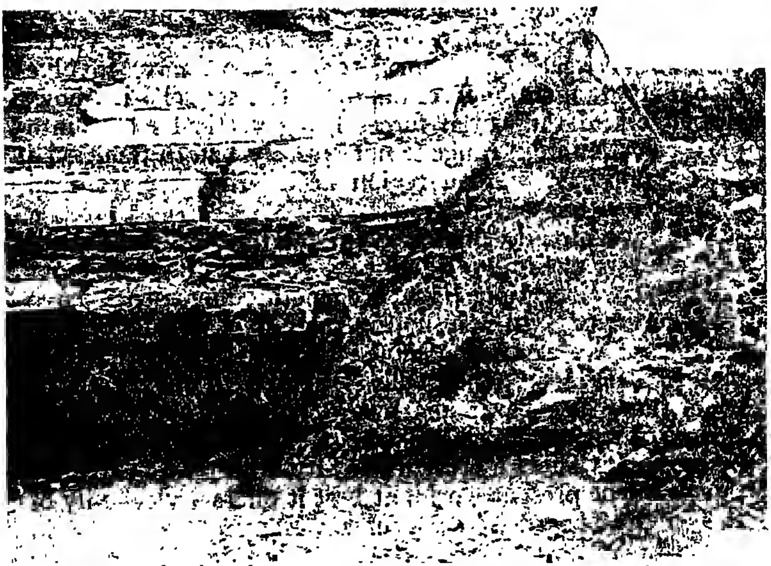
Main types of Earth-Movement

A broad survey of the land areas of the earth indicates two main types of movement. Over wide areas sedimentary rocks have been raised above the sea, retaining an almost undisturbed posture. They underlie many of the larger plain areas, such as the Mississippi Basin or the "Russian platform," and in other cases are elevated so as to build plateau forms, as, for instance, over great areas in the continent of Africa. Here we see the result of radial movements, due to forces acting vertically, which have been styled *epeirogenetic* (continent building or plateau building). Some writers have contended that all such movements take place in a downward sense, towards the centre of the earth, signifying collapse or contraction. On this view the high plateaux of undisturbed strata owe their existence to the subsidence of surrounding tracts and not to uplift. Such a view does not find wide favour to-day. We have already given reasons for supposing that both *isostatic* and *eustatic* movements, both of uplift and depression, may take place (p. 56).

Over rather more limited tracts we find evidence of horizontal movements due to forces acting not vertically but tangentially, to the earth's surface and producing large displacements of the strata. The movements involve either an extension or contraction of the surface according as the forces are tensional or compressional. The effects of such movements are seen in their most advanced stage in the "folded mountain ranges" of the globe, and they have been classed generally as *orogenetic* (mountain-building movements) in distinction from the

[*Photo by H.M. Geol. Survey. Crown copyright reserved.*

FIG. 18.—ANTICLINAL FOLD IN CULM MEASURE SANDSTONE, BUDE, CORNWALL.



[*Photo by H.M. Geol. Survey. Crown copyright reserved.*

FIG. 19.—NORMAL FAULT, THROWING SANDSTONE AGAINST SHALE, CLYDESDALE IRON AND STEEL WORKS, MOSSEND.

epeirogenetic movements mentioned above. The orogenetic movements and forces are sometimes taken to embrace only the contractional or compressive features. Here we include the tensional forces under the heading of orogenesis, since it is difficult to separate them, either in space or time, from the forces of compression, and they certainly produce mountains under certain conditions. Compression in one part of the crust must involve tension in another, and although in one region compressional and tensional conditions may alternate, they must, in the wide view, appear as closely related co-ordinate results of the same general underlying cause.

Accordingly, we may adopt the following broad classification of earth-movements :

Epeirogenetic (radial forces)	
Orogenetic (tangential forces)	*a*. Movements of contraction (forces of compression) *b*. Movements of extension (forces of tension)

Though the two main classes are distinct and worthy of separate recognition, there are certain relations between them. Vertical uplift and depression may involve secondary tangential forces and, as the sequel will show, the effects of tangential forces bring vertical forces into play. A mountain range is not entirely due to tangential forces, nor is a plateau region necessarily free from all evidences of tangential stress.

We have already discussed (p. 53) the nature of some of the larger epeirogenetic movements and may best defer further consideration until orogenetic movements have been surveyed. In considering these it is well to bear in mind that we are not confined to the study of existing mountain ranges. The geologist's view of mountains is wider than the geographer's and includes the survey of the sites of old mountain chains, wholly or partially obliterated by erosion. Though erosion has bitten deep into the lofty ranges of the present world, at best it offers a view only of their more superficial structures. Many older mountain tracts have been so eroded that their internal parts are laid bare; and here much supplementary information may be gained.

Structures due to Compressive Forces

Broadly speaking, compressive forces produce folding and " thrust-faulting " in the crust. Simple folding can be imitated by compressing a pliant sheet of material between the jaws of a vice, or by simply pushing a sheet or pile of sheets against a heavy obstacle. In such experiments an undesirable simplification of the conditions of nature is imported, since the contraction takes place in one direction only. It is essential to remember that rock folding involves a contraction in area, although if the contraction is greater in some directions than others, features resembling those produced by a " one-sided push " will be seen. The conditions of nature are certainly better reproduced by observing the behaviour of a layer adhering to a stretched rubber sheet, when the whole is allowed to contract. In such a case folds are produced,

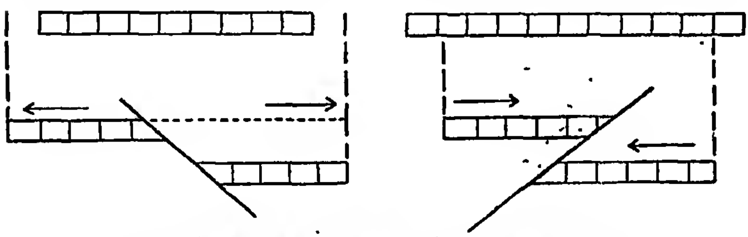


Fig. 20.—Normal and Reversed (or Thrust) Faulting.
Note extension and contraction of surface respectively.

under suitable experimental conditions, and some, at least, of their features of form and spacing resemble natural structures. An alternative mode of contraction is by thrust faulting, as illustrated in Fig. 20. Whether a given rock will fold or fault depends upon its physical properties and upon the magnitude and relations of the forces acting upon it. In general, when the maximum degree of contraction by folding has taken place, a continuance of the force will lead to faulting.

We can arrange structures due to compression in a graded series according to intensity. The first one of the series is open symmetrical folding, a condition rather rarely seen (Fig. 21). The second is the common case of asymmetrical folding in which one limb of each fold is steeper than the other. This implies an element of unilateral, or one-sided, pressure, and it is commonly assumed that the " push " came from the direction of the

gentler slopes, *i.e.* left to right in the diagram (Fig. 21). It is to be observed, however, that a species of underthrust in the opposite direction would account for the facts equally well. From this stage we pass on to the case in which one limb is vertical (Fig. 21). This is sometimes called monoclinal folding, but the term is better restricted, as shown in Chapter VII; such so-called monoclines are really only asymmetrical anticlines. The next stage shows the fold in process of being pushed over on one side, becoming thus an overfold, with both limbs dipping in the same direction. When the two limbs of each fold become parallel the folding is described as isoclinal (Fig. 21); and in the final case the fold becomes recumbent, lying in a roughly horizontal posture (Fig. 21). In the simpler phases of folding the constituent strata do not suffer much stretching within themselves, though there is a tendency to the development of open or gaping joints on the crests of anticlines. With more intense folding the

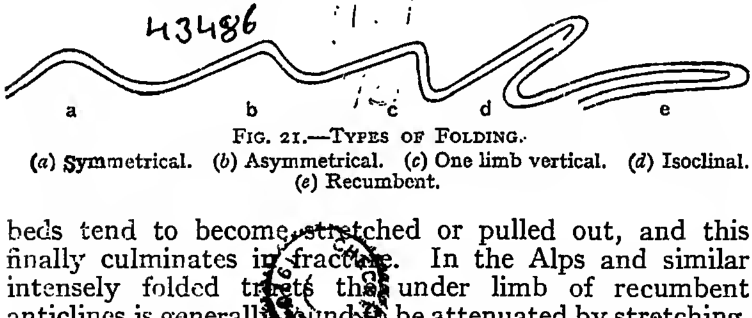
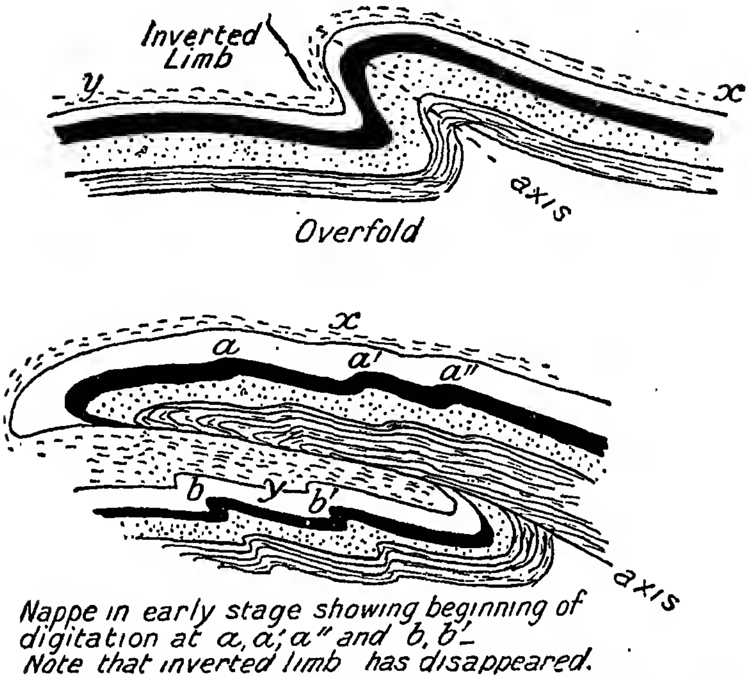


FIG. 21.—TYPES OF FOLDING.

(*a*) Symmetrical. (*b*) Asymmetrical. (*c*) One limb vertical. (*d*) Isoclinal. (*e*) Recumbent.

beds tend to become stretched or pulled out, and this finally culminates in fracture. In the Alps and similar intensely folded tracts the under limb of recumbent anticlines is generally found to be attenuated by stretching, or, if fracture has supervened, a thrust or "slide" takes its place, the upper block moving forward over the lower for great distances (Fig. 22).

Another mode of crustal shortening by thrust faulting is illustrated in the "imbricate structure" of the North-west Highlands of Scotland. Here evidence of recumbent folding is absent, the rocks being disposed in great slices separated by thrust planes, with each slice broken by minor thrust faults more steeply inclined (Fig. 23). The rocks have here behaved like brittle rigid bodies and the effects have been successfully reproduced by H. M. Cadell, who experimented on layers of plaster of Paris interleaved with damp sand (Fig. 24). The application of strong pressure from one side broke the mass into slices along inclined minor thrusts. At a later stage when the



[From Shackleton's "Europe," Longmans, Green and Co

FIG. 22.—DEVELOPMENT OF NAPPE OR RECUMBENT FOLD FROM AN OVERFOLD.

Note also the beginning of minor folds or digitations.

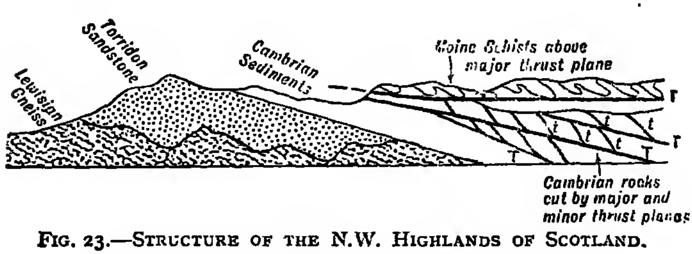
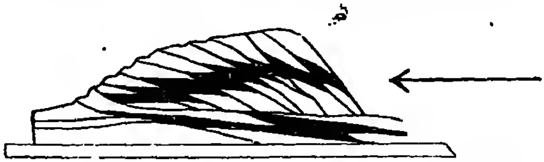


FIG. 23.—STRUCTURE OF THE N.W. HIGHLANDS OF SCOTLAND.
T, major thrust planes; t, minor thrust planes.



[After Cadell.

FIG. 24.—IMBRICATE STRUCTURE.

minor slices had piled up to a certain height more gently inclined major thrusts developed in the mass, and larger blocks rode forward along these.

It is apparent from these facts that structures of widely differing type may result from intense crustal shortening, and it is essential to remember that to interpret such structures on the ground is a much more difficult task than to depict them in a drawing. There have, in fact, been radical differences of opinion about mountain structures. Before the recognition of recumbent folds or nappes (Figs. 22, 29) the Alps were usually interpreted as showing "fan-folding" (Fig. 25). If the student should feel surprise at the possibility of such diverse interpreta-

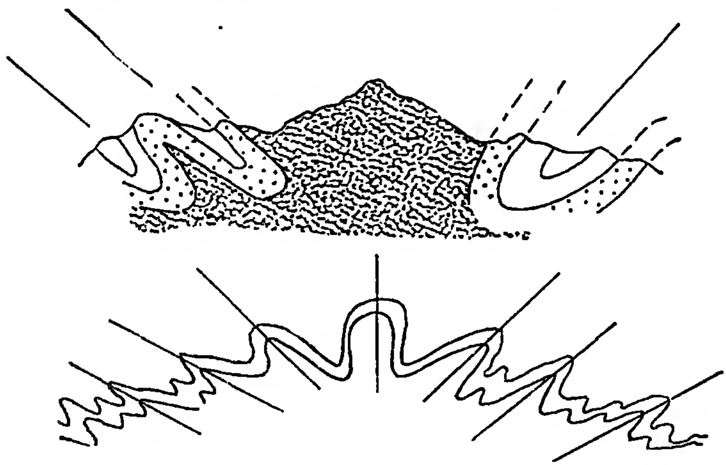


FIG. 25.—FAN FOLDING.

tions of the same observed facts, let him attempt to envisage either arrangement in the field. It will then be realized that the reconstruction of the cross-section of a mountain chain involves the introduction of many features that are not actually seen. The structures are so vast that they extend from far below the valley bottoms to the mountain tops and their completion often involves the reconstruction of vanished portions far above the present peaks. The details of structural complexity are not, however, of great geographical significance, and we can afford, if we wish, to maintain an agnostic attitude on many points at issue. It concerns us rather to treat of the common features in the physique of mountains, which determine their geographical characters.

CHAPTER VI

MOUNTAIN BUILDING

Introductory.—Mountain building by pronounced crustal contraction has not proceeded continuously during the past. The major effects were confined to some half dozen or more short periods of intense crustal stress, separated by quiescent intervals. Localized thus in time, mountain building is not less localized in space, since it has affected only comparatively limited tracts separated by wide areas of little disturbed horizontal or gently folded strata. It has, indeed, been surmised that during the early stages of the earth's history, buckling or creasing of the crust may have been more general, but there is no clear proof of this; it is certain that during the later stages during which the sedimentary rocks of the crust were accumulating, mountain building has been spasmodic.

The plan of mountains as seen on a relatively small-scale map is worthy of attention. In semi-pictorial atlas maps the "caterpillar" type of symbol was formerly popular, but this obscures, rather than reveals, the true relations. In the first place we can distinguish major units, systems, or cordilleras, which often have themselves an arcuate form. Each comprises minor units, ranges, whose course is definitely arcuate, the convex sides of the arcs generally being directed in the same sense. A scalloped pattern is thus imparted to the composite whole; and an analogy is immediately perceptible between the mountain ranges of the land and the "island-arcs" of the continental borders (Fig. 35). The course of both major and minor units often shows an obvious relationship to the position of pre-existing resistant masses, "stable blocks" or massifs, which are often the denuded relics of former mountain systems. Thus in Europe the great arc of the Alps advances between the Massif Central of France on the west and the Czech massif (Bohemia) on the east, while along its front are disposed smaller massifs: Vosges, Black Forest, etc., against, or towards which, it seems to have been pushed. The arc of the Carpathians and the continuing ranges in Eastern Europe are similarly inserted between the Czech massif and the Rumanian "spur" of

the great Russian platform (Fig. 26). It is phenomena of this type which have seemed to justify the assumption of a real wave-like mobility of the crust when under stress, involving great horizontal movements of translation. In the light of the same facts it has been deemed appropriate to speak metaphorically of the " Alpine storm " and of the gentler folds of North-west Europe as its " outer ripples or ground-swell."

In section, considerable variety in structural type appears in mountain ranges. On the one hand we have the comparatively simple folding combined with thrust faulting which characterizes the Appalachians—an ancient and much denuded range (Fig. 144). In a broad sense this may be said to appear also in the Jura of Switzerland, the

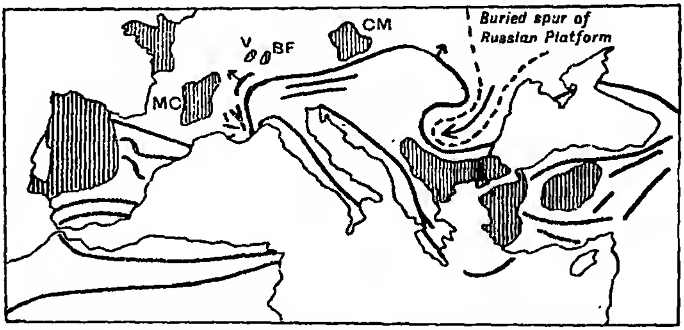


FIG. 26.—RELATION OF ALPINE FOLDS TO OLDER MASSIFS.
MC, Massif Central; V, Vosges; BF, Black Forest; CM, Czech Massif.

Andes and parts of the North American cordillera, as far as they are known. At the other extreme are the enormous complexities demonstrated in the case of the European Alps and believed also to characterize their Asiatic continuations. The Alps have been claimed as the typical mountain system in regard to structure, but the statement is hardly justified in the present state of knowledge. Nevertheless, they may claim pre-eminence in our consideration from the fact that they have been very thoroughly studied and show features of unusual interest.

The structure of the Alps.—We may introduce the complexities of Alpine structure by considering first a simplified section across the French Alps (Fig. 27). Here we find a number of great overfolds leaning towards the north and broken at intervals by major thrusts inclined towards the south. These thrusts divide the system into a number of

structural zones which are as fundamental for the geographer as for the geologist. Thus in the west, overlooking the Rhône valley we have the " External Zone," in which large areas of ancient crystalline rocks (massifs of Belle Donne, Pelvoux, etc.), parts of the floor of Europe on which the later sediments rest, project between infolded areas of Carboniferous and Mesozoic strata. Next in order is the " Briançonnais Zone," separated from the " External Zone " by a great dislocation. Here the western part is based upon Tertiary sandstones (Flysch), while in the eastern part the underlying Jurassic and Triassic limestones emerge and dominate the mountain scenery, with areas of Carboniferous shales and sandstones appearing in the cores of the anticlines. Finally, eastward of another great dislocation, we enter the " Piémont Zone," where the

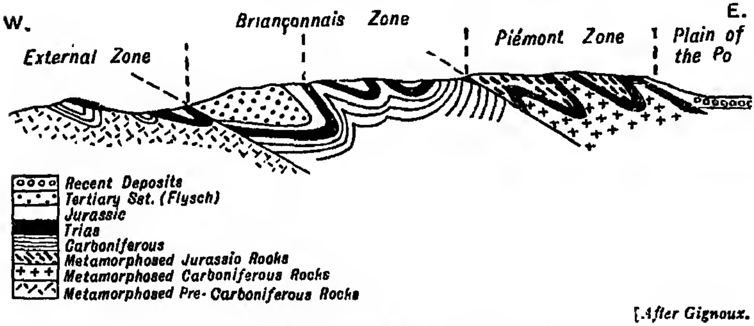
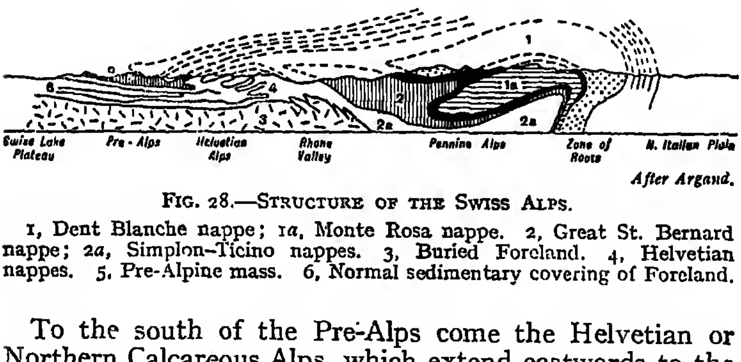


FIG. 27.—STRUCTURE OF THE FRENCH ALPS.

rocks, though originally ordinary sediments of Trassic and Jurassic age, have taken on a crystalline condition under the influence of former deep burial and strong earth-movement, and appear, for the most part, as schists. It is also clear, although the section is greatly simplified, that the structures, folds and faults are on a scale incomparably vaster than the relief forms themselves, which appear as an almost insignificant surface etching of the great folded rock-pile. There is, in fact, no simple relation between major structure and surface.

We may pass on to consider the more extended section presented by the Swiss Alps (Fig. 28). Here, again, a division into structural zones proves possible and, again, it affords the clearest basis for recognition of geographical characters. In the north are the Jura mountains showing relatively simple folding, though broken by large thrusts.

To the south is the Swiss "lake plateau," underlain by Tertiary sandstones, derived in part from the waste of the Alpine ranges during and immediately after their uplift. Next come the Pre-Alps, a group of mountains of inconsiderable elevation and rather subdued topography, which extend along the southern shore of the Lake of Geneva and eastwards to the Rhine. These prove to be built of a pile of flat-lying or recumbent folds or nappes. The rocks of which they are composed cannot be matched in the vicinity, nor anywhere in the Northern or Central Alps. Similar types, however, occur on the Italian side of the chain. A daring hypothesis has therefore found favour, which represents the rocks of the Pre-Alps as having been carried far from the south in great recumbent folds, since eroded away from the higher central regions. The recognition of this gigantic displacement was a vital clue in the elucidation of the structure of the Alps.



After Argand.

FIG. 28.—STRUCTURE OF THE SWISS ALPS.

1, Dent Blanche nappe; 1*a*, Monte Rosa nappe. 2, Great St. Bernard nappe; 2*a*, Simplon–Ticino nappes. 3, Buried Foreland. 4, Helvetian nappes. 5, Pre-Alpine mass. 6, Normal sedimentary covering of Foreland.

To the south of the Pre-Alps come the Helvetian or Northern Calcareous Alps, which extend eastwards to the Rhine through the Bernese Oberland. These, again, are sculptured from a pile of some half-dozen nappes and, since the rocks involved are mainly limestones, the mountains show highly distinctive characters of form, contrasting clearly with the zones both to the north and the south. A detail of their structure is shown in Fig. 29. To the south of the Helvetian Alps, great masses of crystalline rocks, including granites, emerge in places, as in the massif of Mont Blanc and the Aiguilles Rouges and, again, farther east in the Aar–St. Gothard block; these are gigantic splinters of the underlying floor which have been driven up through the piles of nappes—but they do not form a continuous zone at the surface, protruding upwards more in some places than in others. In places, we pass directly from the

Helvetian Alps to the Central or Pennine Alps in crossing the Rhône valley, as in the line of section shown in Fig. 28.

The Pennine Alps are composed mainly of crystalline rocks of a different type, viz. metamorphosed sediments, disposed in six gigantic nappes. In Switzerland these nappes lie in a more or less horizontal posture, and it is only isolated portions of some of the upper members that survive. Thus the famous pyramid of the Matterhorn and the mountains surrounding the Dent Blanche are formed of rocks belonging to the Dent Blanche nappe, resting upon entirely different materials. Beyond the Italian frontier the nappes continue to rise southward for a while, but then plunge downward toward the plain of the Po and are represented as " tucked in under " from the south, much as bedclothes are tucked beneath a mattress. This curious disposition is regarded as the result of collapse or subsidence in the rear region during

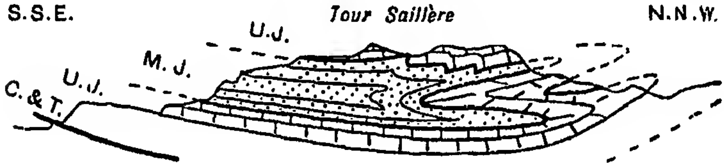


FIG. 29.—THE RECUMBENT FOLD OF THE TOUR SAILLÈRE.
MJ, Middle Jurassic; UJ, Upper Jurassic; C, Cretaceous T, Tertiary.
Major thrust in thick black line.

a late stage of the mountain building, followed by a renewed " under-push " from the south.

Our line of section may be regarded as reaching the Italian Plain east of Turin. Farther to the east another distinct structural zone, that of the Dinarid Alps, comes in and broadens eastwards through the region of the Italian lakes. These mountains, again, are composed largely of calcareous rocks. The zone is separated from the main chain of the Alps by a great dislocation.

East of the line of the Rhine headwaters, through Chur, the Eastern, as distinct from the Western, Alps may be regarded as beginning. Here and eastwards through Austria, the upper nappes, largely removed from the West Alpine pile or preserved only in the Pre-Alps at their northern foot, have been spared by erosion and form much of the surface, the underlying Pennine nappes

appearing from beneath the overlying sheets only in the Engadine and the Tauern region (Fig. 30).

The complexities apparent and implicit in such cross-sections may well prove somewhat staggering to the student, and the mechanics of nappe-formation may seem to defy clear mental formulation. Opinion on this question has, indeed, been very fluid, and finality, either in fact or interpretation, is still far to seek. Nevertheless, the conception of nappes is firmly established, and unlikely to give ground to adverse criticism save in detail. These

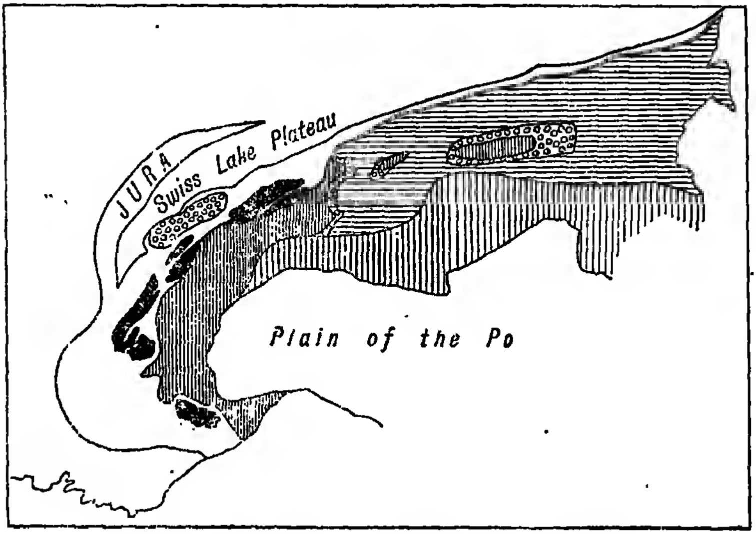


FIG. 30.—SIMPLIFIED STRUCTURAL MAP OF THE ALPS.

Pre-Alpine elements=circles. N. Calcareous Alps=white. Crystalline massifs=black. Pennine (W. Alpine) elements=close vertical lines. East Alpine elements=horizontal lines. Dinarid elements=wide vertical lines.

structures, characterized " by the beauty of their form and the grandeur of their dimensions," are believed by many to reveal the essential unit and method of mountain building, and their Alpine representatives can thus claim much more than a local interest and importance. Before we can deal further with their nature and origin it is necessary to review briefly the earlier history of the Alpine tract and therein to discover principles which apply not only to the Alps but to most, if not all, of the great mountain ranges past and present.

The Geosyncline

One of the most striking features of folded mountain chains is the enormous thickness of sedimentary rocks involved in the folding process. In most cases it is possible to show that the same rock groups are very much thinner under the surrounding plains. For instance, 25,000 feet of sediments are present in the Appalachian mountains, but the same rock groups in the Mississippi region attain a thickness of only 4,000 feet. Similarly, the rock groups of the Alpine chains attain twice or three times the thickness of their equivalents in Britain and Northern Europe. Since it is clearly impossible to explain these great expansions of strata by imaginary accumulation in a gigantic bank we must accept the only alternative, namely, accumulation in a sinking area, which continues to subside as it fills. Such subsidence can be attributed partly, but not wholly, to isostatic adjustment under the weight of the accumulating sediments. Since the area of thick strata coincides with that of the mountain range, the subsiding area must clearly have been long and relatively narrow, *i.e.* trough-like in form. To such an elongated area of subsidence the name *geosyncline* has been applied. The formation and filling of a geosyncline are, apparently, the necessary prelude to the formation of a folded mountain range on the same site. An ancillary condition is the existence of bordering land-masses to supply the sedimentary filling.

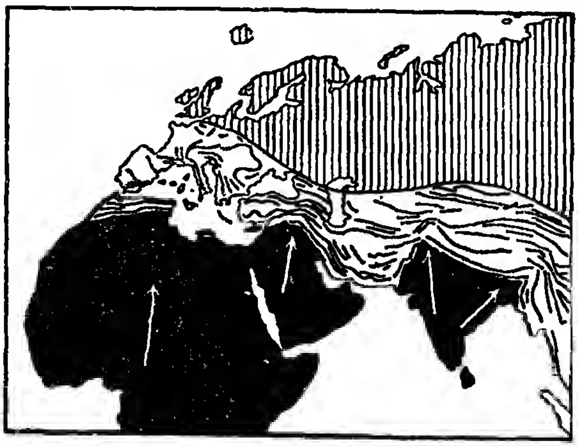
Although the geosyncline idea plays a large part in modern stratigraphical geology, it is by no means easy to recognize convincing examples of such features in the modern world. Some would regard the marginally disposed " deeps " of the Pacific Ocean as actual, or potential, geosynclines, and on a smaller scale we might regard the great valley of California as a feature of the same type, submerged at its southern end; or the Indo–Gangetic Plain as occupying the site of a geosyncline, already partially filled. All these cases, however, differ considerably from the great geosynclines from which the present mountain ranges have arisen, and it is, perhaps, more in harmony with the facts to regard true geosynclines as temporarily absent from the earth's relief plan. However this may be, we can reconstruct the features of past geosynclines in considerable detail.

In the case of the Alps and the related Asiatic ranges,

we can obtain evidence that during Tertiary, Secondary and perhaps earlier times, a wide ocean stretched across the site of part of the Old World land-mass, separating the Eurasian from the African Continent. From time to time shallow epicontinental seas extended beyond its true margins over the continental surfaces and in these comparatively small thicknesses of sediment accumulated. In the main trough, probably not less than 2,000 miles in width, continuous sedimentation went on in generally deeper water; and much larger thicknesses of rock were laid down.

The Hinterland and Foreland

The folding of the contents of the great trough was brought about by the approach of its margins, which

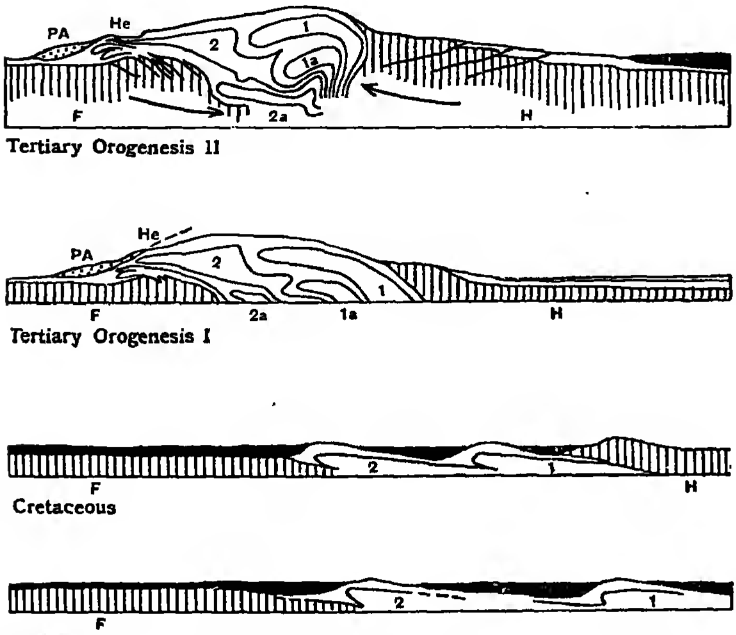


[*After Argand.*

FIG. 31.—THE ORIGIN OF THE TERTIARY MOUNTAINS OF THE OLD WORLD.

acted like the jaws of a vice. The African "hinterland" is believed to have moved northward towards the European "foreland," and the amount of crustal shortening achieved in this gigantic "crush" is estimated as 1,000 miles, or some 15° of latitude. Some geologists have interpreted the phenomena as pointing definitely to continental drift, though it is to be noted that the postulated direction of drift, *i.e.* northwards, is not that which plays the major part in Wegener's hypothesis (Fig. 31). We may, however, be content to defer discussion of ultimate causes; the facts are broadly as stated, however explained, and

they provide a sufficiently remarkable picture. Argand and his followers have outlined a definite series of stages of evolution in the fashioning of the folds (Fig. 32). They believe that the northward thrust of the hinterland produced at a very early stage two major overfolds, which projected above the sea as land masses, or lines of islands, during the deposition of the Secondary deposits, and thus sub-divided the main geosyncline into minor



[*After Argand.*

FIG. 32.—STAGES IN THE ALPINE OROGENESIS.

F, Foreland; H, Hinterland; PA, Pre-Alps; He, Helvetian Alps. 1, Dent Blanche nappe; 1a, Monte Rosa nappe. 2, Great St. Bernard nappe; *2a*, Simplon nappes.

troughs. These two crust waves both moved northwards during Secondary times, the southern one gaining somewhat on the northern. During late Secondary and early Tertiary times the edge of the African hinterland rode rapidly northwards, thus approaching the second of the migrating crustal waves. Finally, in middle Tertiary times, the main paroxysm of earth-movement occurred; the hinterland rode northwards, above the great sedimentary pile which filled the old trough, and, fulfilling

the role of a *traineau écraseur*, or "crushing sledge," dragged the underlying strata into folds of recumbent posture beneath it. Of this series of recumbent folds, the two developed or dragged out crustal waves of earlier date form important members, constituting two of the main nappes of the Pennine Alps. It is, however, conceived that other nappes were developed below each of them by frictional drag and that the drive of the Pennine nappes as a whole developed smaller recumbent folds in the rocks laid down originally near the northern shore of the ocean. These are the nappes of the Helvetian Alps. Gigantic masses of the trough-floor were driven upward in places, through the overlying sediments along the northern front of the Pennine nappes. These form the crystalline massifs of Mont Blanc, etc. The Dinarid Alps represent the hinterland, together with its covering of sediments, originally accumulated near the southern margin of the geosyncline.

At the end of the main phase of orogenesis, the northern edge of the hinterland is believed to have extended completely over the piled up nappes, so as to rest on the foreland, but a succeeding movement remains to be noted. In a late stage there supervened subsidence in the rear region and elevation of the central tracts. Renewed underdrive from the south led to the curious tucking in of the nappes already noted, while later erosion removed the covering of hinterland from the central parts, the only surviving portions forming parts of the Pre-Alps.

The Median Mass

The foregoing account of the structure of the Western Alps, which follows the views of Argand, has, as its central feature, the conception of the northward drive of an African hinterland towards a European foreland with resulting intense compression of the intervening zone. In some respects, however, the Western Alps are not typical of the mountains of the world. A survey of even the immediately surrounding regions, to say nothing of the Asiatic and American mountains, reveals features absent or inconspicuous in the Alps, particularly in respect of arrangement in plan or symmetry in cross-section. Kober, from studies over a wide field, conceives the typical "orogen," as shown in Fig. 33. In his view an orogenic belt shows, normally, not a foreland and a hinterland but

rather two forelands, one on each side, with overthrusting towards both. Between the bordering ranges thus thrust outward, occur *Zwischengebirge* (betwixt-mountains) of simpler structure. We may note that even in the Alps there is evidence of thrusting in opposed directions, for the great thrusts of the Dinarid ranges indicate a movement towards the south, contrasting with the evident northward movement along the edge of the European foreland. There is, however, no feature in the Alps which we can identify with the "betwixt-mountains." Nevertheless, Kober's conception appears to be of much more general application than that used by Argand in the Alps. In particular, intermontane areas of simpler structure, analogous to Kober's *Zwischengebirge*, prove to be of common occurrence and are certainly a systematic or repeating element in mountain architecture. Since, however, the intermontane tract is not necessarily mountainous in relief, but may show a variety of topographic forms, it is certainly better to use the more general term "median mass" in place of *Zwischengebirge*.

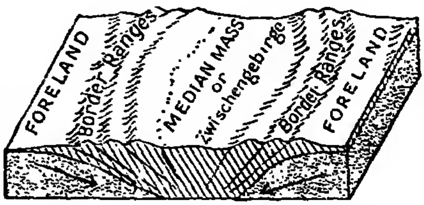


FIG. 33.—THE TYPICAL "OROGEN" ACCORDING TO KOBER.

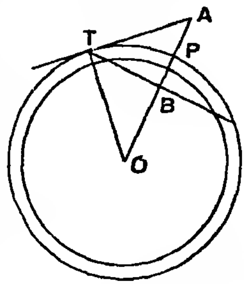
According to Kober's reading of Alpine structure, "median masses" occur in the Mediterranean region between the northern, or Alpid, and southern, or Dinarid, sides of the Alpine belt. One such mass he regards as largely submerged beneath the Western Mediterranean, though it includes parts of Corsica and Sardinia. The Hungarian Plain (Pannonian Basin), between the arc of the Carpathians and the Dinaric ranges of the Balkans, forms another median mass, while the Rhodope Plateau of the Balkans and its eastward continuation into Anatolia forms a third. Still further east in Persia, a typical median mass has been recognized between the Iranian ranges and the Elburz ranges. In the Balkans, Asia Minor and in Persia the median masses form upland country, thus contrasting with their low-lying or submerged analogues farther west. Though structural details are at present lacking for most other parts of the world, we may note that the Caribbean Sea appears to be a submerged median

area, lying between the Central American chains and the West Indian arc, and the Mexican Plateau may be of a similar nature. So far as plan and general morphology are concerned, the Basin-Range region of Nevada, lying between the Sierra Nevada and Wasatch ranges, seems to form an admirable example of a median mass. The characteristic "basin-range structure," consisting of tilted fault blocks (Fig. 193), and the great fissure-eruptions (p. 114) farther north, may yet prove to be characteristic features of median areas. The great high-level mountain-girt basins of Central Asia also suggest themselves as comparable features, though the structure of the enclosing ranges is not yet known with sufficient certainty to render possible a full comparison with the supposed typical orogen.

Before we leave the conception of the typical orogen with its median mass we may note that the primary movements involved in its formation are the vice-like inwardly directed underthrusts of the two foreland jaws—*i.e.* there is an inward motion below, acting as the prime cause of the outward thrusting above. Such an idea in its simple form is not incompatible with any of the main mountain-building theories reviewed below, and is clearly susceptible of variations in detail, according to the relative magnitude of the two underthrusts. In the Western Alps it is clear that a strong "one-sided" element has entered, if current ideas are sound, and thus the simple symmetry has been destroyed. We may, however, generally expect to find a distinctive intermontane area, or median mass, which, though it may vary in width and locally disappear altogether, is a distinctive feature of mountain morphology.

Island Arcs.—The arcuate lines of islands which are so conspicuous a feature of the Western Pacific area are generally interpreted, following Suess, as the unsubmerged tops of young folded mountain chains, effectively continuous with those of the mainland. That such is true in the majority of cases can hardly be doubted, though some of them (notably the Japanese arc) appear to be more complex than this theory allows. In the case of mountain arcs, such as that of the Carpathians, the form approximates closely to a circular arc in many cases. This important fact may be simply explained if the arcuate "crease" has ridden forward along a thrust-plane, for a true plane intersects a sphere in the arc of a circle. It is known with certainty that many of the mountain arcs

are based upon one or more thrust-planes. The Carpathian arc has ridden northward over the Silesian coal-field, partially covering the coal-bearing beds, and the Himalayan arc is margined along its southern side by thrusts along which it has travelled southward. Such a relation is, indeed, the normal one along the edge of a folded belt where the frontal folds are driven over on to the foreland. The simple geometry of the case is such that, for any circular arc due to the emergence of a thrust-plane at the surface of the earth, the angle of inclination of the thrust is equal to the radius of the arc measured in degrees—*i.e.* the angle subtended at the centre of the earth by the radius (Fig. 34). It has been shown by Lake that the revised observations of the inclination of the Himalayan thrust agree very closely with the computed value on this hypothesis.



[*After Lake.*

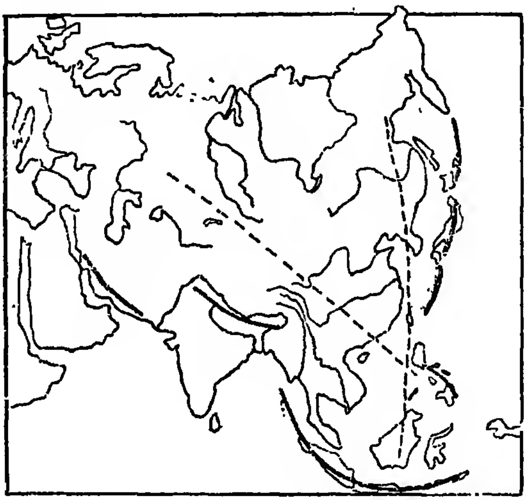
FIG. 34.—THE GEOMETRY OF A MAJOR THRUST PLANE.

BT is plane of thrust emerging at T; P is pole of arc made by outcrop of thrust plane; Angle ATB=Angle AOT.

Many island arcs are also nearly circular in form, notably the Aleutian arc and the East Indian arc as far east as the Banda Sea. In detail, of course, the arc is not a line, and it is necessary to select some one guiding feature to represent it approximately. Lake has shown that the poles of several of the island arcs of East Asia lie close to the same great circle (Fig. 35). If we assume that each is based upon a thrust-plane, these thrust-planes will all lie at right angles to the great circle in question (Fig. 34) and we are led to envisage a creep of Eastern Asia over the floor of the Pacific along this series of related thrust-planes. Similarly, if the Iranian, Himalayan, and East Indian arcs be considered, their respective poles are found to lie close to another great circle (Fig. 35) and, on the hypothesis of basal thrust-planes, one may infer a southward creep of the southern edge of Asia over the floor of the Indian Ocean. We thus obtain a strong suggestion of movement of the edges of the Asiatic Continent towards the east and south-west respectively. Clearly the mass as a whole cannot move in both directions, and an under-thrusting from the ocean floor, kindred to the under-thrusting conceived by Kober to take place along the margin of his orogen, probably affords a

better description of the process. Such under-thrusting is entirely compatible with certain theories of mountain-building mentioned in Chapter IX. Suess originally regarded the arcs as indicative of a force operating from the continental interior towards the ocean border, but quite apart from the important facts recently advanced by Lake, Hobbs has adduced a number of other reasons for regarding the thrust as transmitted inwards from the ocean floor.

Phases in mountain building.—Though the Alps appear to possess certain unique elements of complexity, the general history of the formation of the chain shows certain



[*After Lake.*

FIG. 35.—ISLAND- AND MOUNTAIN-ARCS IN ASIA.

The poles of the arcs fall on or near the dotted lines shown, which are great circles on the sphere.

systematic features common with those of other regions. In the first place, it is clear that we can divide the period of mountain making in the wide sense into three phases as follows :

(1) The period of lithogenesis, during which the rocks later to form the range are accumulated in the subsiding geosyncline.
(2) The period of orogenesis, during which the accumulated rocks are strongly compressed, with resultant folding and faulting.
(3) The period of glyptogenesis, during which the

characteristic surface forms are sculptured by erosion.

Looking at the matter in more detail we may say that the pre-requisite condition for the start of the mountain-building process is the existence of a low-lying tract, generally, though not necessarily, submerged beneath the sea, into which sediments are brought from bordering higher lands. There ensues, in the first place, a subsidence of the loaded tract under the weight of the accumulating sediments, or "sedimentation-subsidence." To such a process, however, there is a very definite limit and the whole of the subsidence cannot be explained in this way. The principles of isostasy lead us to suppose that the outer sial layer of the crust is relatively thin beneath the low-lying geosynclinal area, and hence the depression of the area must involve the displacement of the sima below, which presumably flows towards the margins, helping to buoy them up. Since the accumulating sediments are, however, much lighter than the sima, it is clear that very definite limits are set to the possibilities of "sedimentation-subsidence," and it is comparatively simple to calculate the extent of depression so caused. In actual fact, far greater thicknesses of sediment have accumulated in geosynclines than can be accounted for by sedimentary loading alone; and we are accordingly forced to seek some other cause of depression. There is little doubt that we must find it in the fact that compression has already begun, bending down the floor of the growing trough and bringing the two margins or jaws nearer together. To this process we may apply the term "compression-subsidence." This process of narrowing and deepening proceeds, but the trough fills, on the whole, faster than it deepens, so that eventually it becomes full of sediment. With further contraction the true orogenesis starts. The sedimentary infilling is thrown into folds and, later, great thrust-faults develop, while the floor itself may be broken and pushed up into the mass. It will be observed that the effect of this process is still further to load the depressed area; the sedimentary pile is thickened by the piling of sheet upon sheet, whether by recumbent folding, thrust-faulting, or both. This probably leads at first to further subsidence, a "folding- or faulting-subsidence." But the result of the continuing subsidence has been to drive rocks of low density down into the sima, with resultant displacement of the latter. However far the crests of the rock-folds project

above the general level at the end of the orogenesis, they project much farther below. The resulting pile has got to attain isostatic or floating equilibrium ultimately. While the compression continues the downward projection of the pile may be literally held down by pressure at the sides. Thus if we depress a wooden block below its normal floating position we can maintain this only by placing a weight on top of it or by pressing hard from opposite directions against its sides. When compression is relaxed there must be a tendency for the whole pile of folds to rise, or to be floated up. Thus it is that late in the mountain-building process, long after the folds and faults are formed, there commonly follows uplift.[1] Another fact to be remembered in this connexion is that the lower portions of the great pile have been depressed into regions of high temperature, and must thus expand. Some writers attribute considerable importance to this thermal expansion of the "roots" of mountains in causing actual uplift. Whatever be the relative effect of these two causes of uplift, it is a fact of major importance, on which general agreement has been reached, that the horizontal compression and the vertical uplift of a mountain range are, in large part, distinct and successive processes. The piling together of the rock-sheets would undoubtedly lead to some sort of elevated surface feature, but the height to which existing ranges project above the plains points definitely to some later vertical uplift, or "humping," in the central tracts. The extra height thus imposed upon the mountain-tract is, clearly, a factor of great importance in leading to rapid sculpture of the piled and uplifted mass by water and by ice. The enormous destruction already wrought upon the recently uplifted Alpine pile constitutes one of the most impressive features of that remarkable range; and it is here of significance that, in parts of the Western Alps, erosion has removed rock-sheets some eight or nine miles thick, whereas in the Eastern Alps, where the underlying floor of the geosyncline was lower than in the west, the rock-sheets were piled less high, and were, in consequence, less exposed to denudation.

Old mountains.—In the foregoing paragraphs we have considered the structure and mode of formation of what

[1] The first effect of such uplift is to restore the folded pile to a condition of isostatic equilibrium, but after this stage is reached uplift may still continue concurrently with the destruction of the mountains by denudation and the resultant lightening of the "mountain column" (cf. p. 28).

are often classed in geographical literature as the "young folded mountain ranges." These are the true mountains, *par excellence*, of the present world, outstanding in elevation, extent, grandeur and variety of form. It is evident, however, that the term mountain, in its wide sense, is considered equally applicable to other types of elevation, such as are provided by the outpourings of volcanoes or the edges of tilted earth blocks. These are so obviously different in form and origin and, in general, of so much less importance that no confusion need arise in conceding them the name of mountain. A distinction of much greater importance, however, is that which must be drawn between young folded mountain ranges and what, for the sake of brevity, we may for the present term "old mountains."

A consideration of the past history of the earth makes it clear that mountain ranges whose extent and elevation rivalled those of the present Alps have been entirely obliterated by erosion. The geological characteristics of mountains are, however, more fundamental and less temporary than their geographical features, in the narrow sense. Though the relief forms may disappear, the structures continue to depths beyond the reach of erosion. In a group of mountains extensively worn down by erosion, or even "reduced to a peneplain" (p. 183), all semblance of the original form is lost; but the folded rock-sheets and the great fractures which separate them may still be clearly discernible and may still figure as important factors in the geography of the country, separating terrains of different rock-constitution, scenery, hydrography, and mineral wealth. It is, in fact, possible in such areas as the Canadian Shield, West Africa, etc., to trace the "trend lines" of very ancient ranges across low-lying tracts. Moreover, uplift of such an area may lead to a kind of rejuvenation of the old mountains, erosion re-etching the mass and giving us again a mountainous relief. Though such "secondary" mountains may bear some resemblance to their ancestors, their origin, and therefore their characters, are entirely different in many respects, and from the geographical standpoint they form a distinct class.

We may take as an example the mountains of Scotland (Fig. 36). Even cursory examination shows that the rocks are highly disturbed and, though their detail is difficult to decipher, it is claimed that great nappes of

the Alpine type can be traced. The mountains themselves bear no simple relation to the major rock-folds, but, as we have already noted, the same is true of the Alps. Wherein, then, lies the difference in their history? A clue is obtained on viewing a portion of the mass from one of the higher summits. It is at once evident that the peaks reach a very uniform elevation and show evidence of having been sculptured from an initially level surface (p. 216). The geological history of the district, as deduced from other evidence, is in harmony with this conclusion. Though the structures are extremely old the mountains are comparatively young. The original mountains formed at the time of the folding succumbed, in course of time, to atmospheric attack and over their site an extensive plain stretched; indeed, portions of the area were submerged and received a cover of marine sediment. In much later times the area has been subject to uniform uplift without

[*After Peach and Horne*.

FIG. 36.—GENERALIZED SECTION ACROSS THE HIGHLANDS OF SCOTLAND. The relation of folds and thrusts to the present surface.

appreciable folding, though some faulting has taken place. From the uplifted mass the present relief has been carved. The Scottish mountains thus form a dissected plateau and, in part at least, belong to the class called by some writers "mountains of circum-denudation." The same is true of the mountains of Wales, where the plateau-like aspect of the summit plane is even more striking.

A further striking example of the partial rejuvenation of ancient mountains is afforded by the Altaid mountain system, of which the Armorican and Hercynian folds of Europe and the Appalachian folds of America formed constituent parts. At the time of their formation, at the end of Carboniferous times, the Altaid mountains stretched almost completely across the Old World land block, from Central Asia to Western Europe; and these ranges were probably continuous with their American analogues, now separated from them by the Atlantic Ocean. Though the original relief forms have entirely disappeared, the trend lines of the system are readily traceable (Fig. 37).

In Europe, they provide an invaluable key to the regional geography of many tracts, rendering evident the continuity of the belts of coalfields preserved in the old synclines. The present topographic form of the old mountain zone varies considerably from place to place. In the Appalachians uplift and re-etching have given us mountains of the dissected plateau type. In south-east England the mountain folds are buried deep beneath later accumulations of sediment. The same sedimentary cover extends over the neighbouring plains of Northern and Central Europe where the Altaid (Armorican or Hercynian) " floor " projects in blocks of uplands as in the

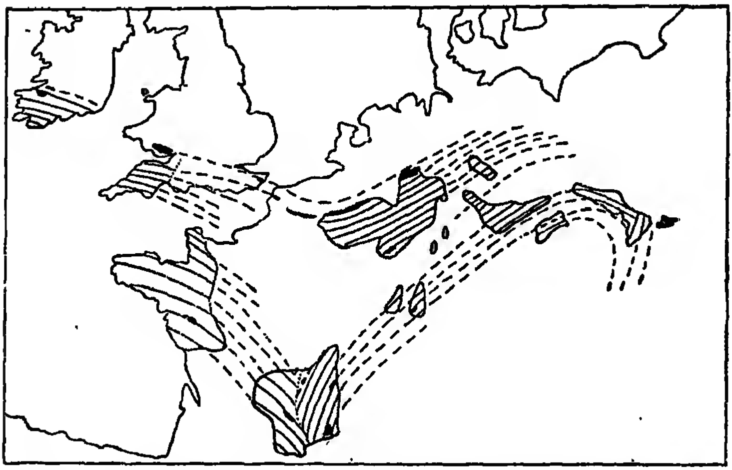


FIG. 37.—THE TREND LINES OF THE ARMORICAN–HERCYNIAN FOLDS IN EUROPE.
Coalfields shown in black.

Armorican Massif of North-west France, the Massif Central, the Rhine Slate Plateau, the Vosges, the Black Forest, and the Czech or Bohemian Massif. All these blocks of upland show highly disturbed rocks, folded and, in some cases, metamorphosed during the Altaid orogenesis. They owe their present upstanding relations to later movements of broad warping or folding, or to the down-faulting of neighbouring lands. Many of them projected as island masses above the shallow seas which covered the European plains in Secondary times. As already noted, they stood as bastions against the advancing Alpine folds of a later day ; and some of them were further

raised above the surrounding plains in the general disturbance or "ground swell" caused by these movements. They survive to-day as salient elements in the geography of Europe: the "massifs" of some writers, the "block-mountains," "uplands" or "horsts" of others, connected with one another, beneath the sedimentary cover of the intervening plains, by the fold-lines of the ancient and vanished mountains.

The significant geographical differences between young fold mountains and uplands of the dissected-plateau type reside largely in the character and texture of relief. The former attain much greater elevations as a general rule. Their relief forms are more youthful and perhaps less perfectly adapted to the detail of rock structure. Through valleys, transverse to the general grain, are subordinate, but in mountains of the Scottish type they are commoner, being eroded along fault-lines and shatter-belts of later date than the original folding. Though these several contrasts are real and important we must recognize certain important points of similarity; in particular, the same division into blocks or structural zones by the major lines of dislocation can be recognized in both cases. In Scotland the Great Glen marks such a line of dislocation, and it may be compared with similar longitudinal depressions such as that which contains the headwaters of the Rhine and the Rhône in the Alps. Glaciation has often modified relief in regions of both types and in such cases further similarities are imported.

The succession of mountain-building episodes.—We have already noted that mountain building takes place in definite and limited areas at widely separated periods of time. The mountain-building episodes or "revolutions" punctuate the record of earth history and, for the geologist, provide a natural basis for sub-division of geological time. Each in turn has drastically re-modelled the distribution of land and sea and the relief of the continents, and has thus affected the course of biological evolution. For the geographer a recognition of the several successive phases of orogenesis is hardly less important, inasmuch as the structure of the present continents is a mosaic of elements, many of them referable to one or other of the ancient mountain systems. In Britain and Western Europe we can clearly recognize three major periods of mountain making (the Caledonian, the Altaid and the Alpine) as well as others of the more distant past less

clearly decipherable also a number of minor phases of folding. The chronological position of the three main phases is illustrated in Fig. 38, which shows their relation to the main geological periods. Their respective contributions to the structure of Europe are indicated in Fig. 39.

The Caledonian ranges occupied the site of Northern Ireland and the Highlands of Scotland and continued north-eastward through the Scandinavian Peninsula. The north-western limit of the folded tract closely parallels the north-western coast of Scotland, the Hebrides being remnants of the ancient foreland. The south-eastern limit in Scandinavia is the famous "glint-line," along which the folded terrain adjoins the Baltic or Fenno-Scandian block, which functioned as the hinterland in the original folding. It is the basal ruins only of this great range which figure to-day in the relief of Northern Europe.

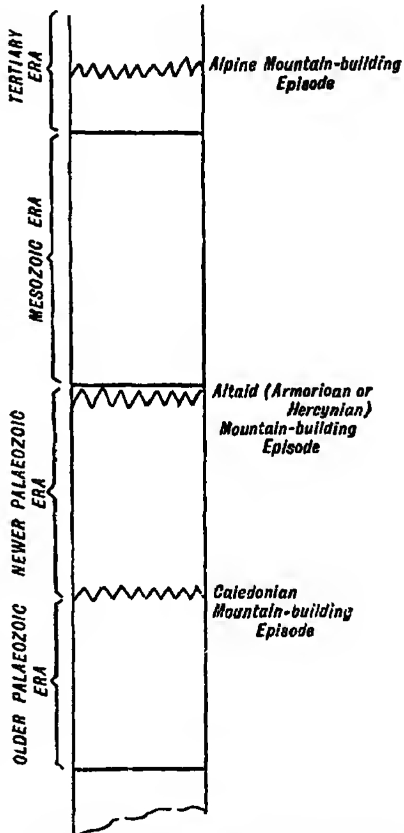


FIG. 38.—THE TIME-RELATIONS OF THE CHIEF MOUNTAIN-BUILDING PERIODS.

The course and varying topographic expression of the Altaid folds has already been indicated. They lie for the most part south of the Caledonian folds, encroaching upon or over-riding them only in Southern Ireland. Similarly, they follow a course to the north of the later Alpine folds, though the planed-down remnants of their southern parts underlie the Alps and have, to some extent, been involved in the later movements. The relation of the Alpine fold-lines to the surviving stable elements in Europe has already been indicated. Thus the continent of Europe

embraces three converging and overlapping series of mountain folds of widely different date, each formed, on the whole, to the south of its predecessor.

The successive periods of mountain building have contributed further to the geographical make-up of Europe, by providing conditions for the formation of metallic ores. By far the greater number of the world's ore bodies, of the mineral-vein type, are associated in time with the mountain-building periods, which are also periods of metallogenesis.

The growth of structures.—The foregoing review of the mountain-building process suggests that, viewed on a

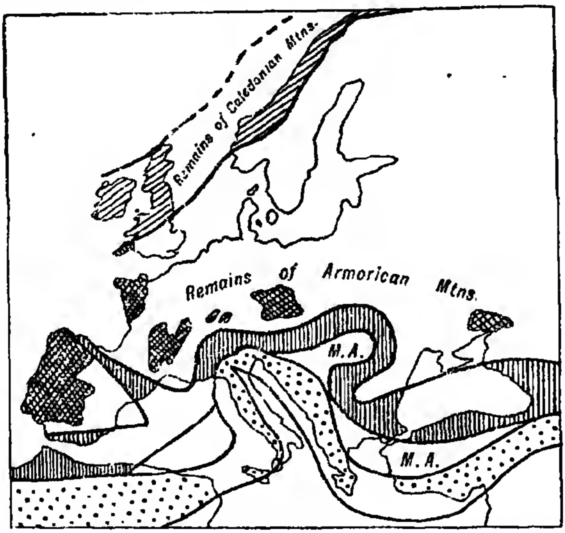


FIG. 39.—THE MOUNTAINS OF EUROPE.
Main Alpine elements=vertical shading; Dinarid elements=dotted; MA=median area.

broad scale, folding movements are comparatively sudden events, separated by intervals of quiescence. The general truth of this statement must not blind us to the equally important fact that, scrutinized closely and individually, many structures show evidence of slow and long continued growth. Argand's synthesis (p. 77) represents two of the major recumbent folds of the Alps as having been initiated long before, as simple crustal ripples (Fig. 32), and the principle there illustrated can be demonstrated even more completely in regions of simpler structure. The region north of the main Alpine folds, embracing much of Central

and Western Europe and a large part of the British Isles, shows a general cover of Mesozoic and Tertiary rocks of moderate thickness, resting on the planed-down Hercynian floor, which, as we have seen, locally emerges in the form of " island massifs." The cover rocks show gentle folding and local faulting which is broadly contemporary in date with the folding of the Alps. The region belongs, in fact, to a type which we might call " regions of tectonic ground swell," [1] lying intermediate, in point of structural complexity, between the storm areas of the fold mountains and the quiescent tracts of flat-lying strata.

In reviewing the structures of such a region a problem immediately arises as to the relation between the structures of the cover rocks and the structures of the " floor." Are we to assume that the latter is bent into a form concordant with surface structures, or do those structures die out in depth? It may be said at once that there is no one simple answer to this question. In regions of simple structure we can often study not only the surface geology but the underground geology as revealed in wells and borings. By such means it has proved possible to study the underground continuation of surface structures and to arrive at certain principles of great importance and wide application.

The first principle emerging from such studies may be termed that of " posthumous folding." Under certain circumstances a line of folding, once established, shows great longevity or recurring instability. Thus a superficial anticline in cover rocks may be found to coincide in position with an older flexure in the floor. The surface structure represents " posthumous movement " along the older line and the form of the floor accords broadly with the surface structure. Thus it has been held that some of the main anticlinal flexures of Southern England, dating from the time of the Alpine movements, reflect posthumous movement of buried Hercynian anticlines. In the west, in Devon, Cornwall, and South Wales, the latter emerge at the surface. Eastwards they plunge beneath the " cover," but their line is continued by superficial structures.[2] A posthumous relation of this kind is

[1] It is structural regions of this type which give rise, under denudation, to the " scarpland type " of morphological regions (p. 197).

[2] Thus an anticlinal fold which follows the northern edge of the Weald from near Guildford to Hythe is believed to mark the position of the continuation of the " Mendip axis " in the floor.

likely to characterize regions where the cover is relatively thin, and it may embrace other types of structure than anticlinal folds. Thus around London, where the cover-rocks are little more than 1,000 feet thick over a considerable area, the slight superficial flexures may well reflect renewed movements along old faults in the floor. The arrangement may be likened to that of a thin slice of plasticine resting on parquet flooring. If the joints of the latter shift in response to pressure, the slice will accommodate itself to the changing form beneath.

A second principle of high interest concerns those cases in which it can be shown that folding movements took place concurrently with the deposition of the rocks involved in the fold. Such a relationship can often be demonstrated by reference to the thickness and lithological character of the sediments studied over a considerable region. Under shallow-water conditions, a region of locally rising sea-floor, *i.e.* a growing anticline, tends to receive a smaller thickness of sediment than neighbouring "downwarped" areas. Even if the supply of sediment be everywhere equal, the uplift may raise the sea-bed into the zone of wave or current scour, which removes unconsolidated sediment from the crest of the fold, while uninterrupted accumulation proceeds in undisturbed water on the flanks. Actual emergence, followed by denudation, may result if the uplift is rapid. We hardly know enough of the conditions of shallow sea-floors to enable a direct investigation of such possibilities, but the geological evidence often tells so consistent a story as to leave little choice of conclusion. A condition frequently realized is illustrated simply in Fig. 40, where each stratum thins towards the crest of the anticline. This may be illustrated in section, but conclusions may be more soundly based if we draw *isopachytes*—lines of equal (original) thickness—for each of the beds, obtaining our data from the records of wells and borings. By such means it has been conclusively demonstrated that many folds which reveal their presence in the existing structures and form of the landscape have a long antecedent history and controlled the topography of vanished sea-floors. Thus, a gentle line of anticlinal flexuring traverses the northern side of the London basin from south-west to north-east, bringing up inliers of chalk at Windsor and Northaw. Along this belt the lower Tertiary strata are exceptionally thin, whence we conclude that the fold was initiated in Lower

Tertiary time or earlier, though it did not come to completion until the time of the Middle Tertiary Alpine movement. Summarily, then, we may say that isopachyte maps often present us with pictures of growing structures. Their testimony may often be supplemented by that of maps which show " changes of facies " in rocks of the same age, for shallow water accumulations tend to mark the rising areas, giving place to the deposits of deeper water in the subsiding troughs.

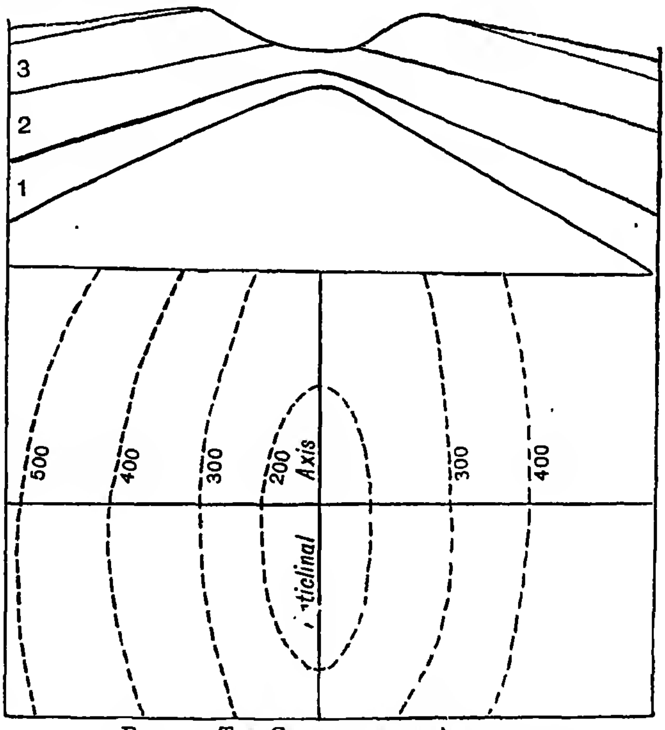


FIG. 40.—THE GROWTH OF AN ANTICLINE.
The map shows isopachytes for bed 2 of the section.

A third principle encountered in studies of sub-surface geology is in reality not new; it is the " geosyncline principle," illustrated in major mountain building (p. 75), but here illustrated on a smaller scale. Where the cover-rocks of North Western Europe become relatively thick, *i.e.* where the floor descends into the form of a trough, the trough filling has been thrown into folds by compression,

just as in the case of a major mountain range. An admirable example is offered by the Weald—structurally a veritable mountain range in miniature. Beneath the Weald the "floor" descends to undetermined depths, which must certainly exceed 4,000 feet. The thick filling of this minor geosyncline was thrown into east-west folds at the time of the Alpine movements. Such structures bear no necessary relation to the structures of the underlying floor, being dependent merely on the form and trend of the trough. The Wealden folds happen to trend east to west, roughly parallel with the direction of the floor structures, but in other similar cases in North-west Germany the trend of the trough is across the line of the floor structures, and the surface folds are hence unrelated to the latter.

A full discussion of the topics here briefly introduced would carry us far beyond the field immediately relevant to this work; they constitute one of the most modern developments of stratigraphical geology. Nevertheless, the general principles involved are of interest both to the geomorphologist and the geographer. Broadly speaking, we perceive a strong tendency for structural patterns to repeat themselves from age to age.

CHAPTER VII

TENSION IN THE CRUST OF THE EARTH

Our knowledge of the tensional forces and their effect is less satisfactory, or less completely formulated, than that of compression. Nevertheless, it is reasonable to assume that tensional forces must operate, for compression in one region must generally involve tension elsewhere. Moreover, structures exist the origin of which demands the operation of tensional forces, either local or regional.

Local tension : joints.—Local tension occurs during the cooling and consolidation of igneous rocks ; the drying of ordinary sediments ; and the crystallization of such rocks as limestones. The result is the production of systems of joints. If a rock were free to contract during cooling or desiccation no tendency to actual splitting would exist, but since it is commonly in contact below, and possibly also above, with other masses which do not share in, but resist, the contraction, tension and ultimate splitting result. Tension joints also form parallel to the unsupported edges of cliffs or escarpments. Local tension exists on the stretched crest of an anticline, and under these conditions widely gaping joints are sometimes formed which materially assist the process of erosion. The same tension would, of course, exist on the underside of a syncline, but here, owing to the pressure of surrounding rocks, open joints are less likely to be formed. All these local tensional forces are of relatively small magnitude, but the jointing systems produced are natural avenues for the attack of weathering and erosion and do much to control both the detail of scenery and the technique of quarrying and mining operations. These related sets of joints commonly occur respectively parallel to the bedding, the strike, and the dip of the rock, but more complex series exist ; thus rocks may be traversed by two or more systems of joints developed at different times.

Further, joints may develop in other ways, particularly under conditions of torsion or twisting, such as must commonly occur in much disturbed regions (see further at p. 130).

Regional tension : faults.—Regional tension commonly

just as in the case of a major mountain range. An admirable example is offered by the Weald—structurally a veritable mountain range in miniature. Beneath the Weald the "floor" descends to undetermined depths, which must certainly exceed 4,000 feet. The thick filling of this minor geosyncline was thrown into east-west folds at the time of the Alpine movements. Such structures bear no necessary relation to the structures of the underlying floor, being dependent merely on the form and trend of the trough. The Wealden folds happen to trend east to west, roughly parallel with the direction of the floor structures, but in other similar cases in North-west Germany the trend of the trough is across the line of the floor structures, and the surface folds are hence unrelated to the latter.

A full discussion of the topics here briefly introduced would carry us far beyond the field immediately relevant to this work; they constitute one of the most modern developments of stratigraphical geology. Nevertheless, the general principles involved are of interest both to the geomorphologist and the geographer. Broadly speaking, we perceive a strong tendency for structural patterns to repeat themselves from age to age.

CHAPTER VII

TENSION IN THE CRUST OF THE EARTH

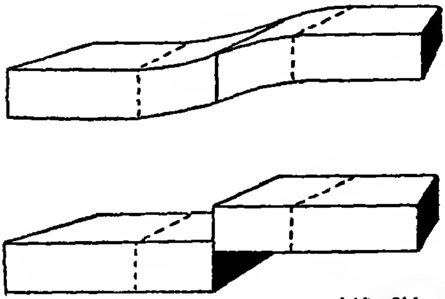
Our knowledge of the tensional forces and their effect is less satisfactory, or less completely formulated, than that of compression. Nevertheless, it is reasonable to assume that tensional forces must operate, for compression in one region must generally involve tension elsewhere. Moreover, structures exist the origin of which demands the operation of tensional forces, either local or regional.

Local tension : joints.—Local tension occurs during the cooling and consolidation of igneous rocks ; the drying of ordinary sediments ; and the crystallization of such rocks as limestones. The result is the production of systems of joints. If a rock were free to contract during cooling or desiccation no tendency to actual splitting would exist, but since it is commonly in contact below, and possibly also above, with other masses which do not share in, but resist, the contraction, tension and ultimate splitting result. Tension joints also form parallel to the unsupported edges of cliffs or escarpments. Local tension exists on the stretched crest of an anticline, and under these conditions widely gaping joints are sometimes formed which materially assist the process of erosion. The same tension would, of course, exist on the underside of a syncline, but here, owing to the pressure of surrounding rocks, open joints are less likely to be formed. All these local tensional forces are of relatively small magnitude, but the jointing systems produced are natural avenues for the attack of weathering and erosion and do much to control both the detail of scenery and the technique of quarrying and mining operations. These related sets of joints commonly occur respectively parallel to the bedding, the strike, and the dip of the rock, but more complex series exist ; thus rocks may be traversed by two or more systems of joints developed at different times.

Further, joints may develop in other ways, particularly under conditions of torsion or twisting, such as must commonly occur in much disturbed regions (see further at p. 130).

Regional tension : faults.—Regional tension commonly

expresses itself in what is known as "normal" or "gravity" faulting. Figs. 20 and 41 illustrate the nature of such faulting, in which one block has slipped down relatively to the other along a steeply inclined plane. Such a movement implies an extension of surface area, as contrasted with the contraction associated with "reversed faulting." The cross-section of a normal fault as it appears on the page of a text book, or in cliff or quarry section, is apt to be misleading. It must be remembered that the movement takes place in three, not in two, dimensions and that the extent of slipping (the "downthrow") is not the same at all points along the fault-plane. There is commonly some rotational movement of the down-faulted block and, sometimes, as a result, the direction of downthrow changes, as is illustrated in Fig. 42. Also there may be purely horizontal, as well as vertical, movement along the fault-plane, as was illustrated by recent movements along the San Andreas fault[1] (p. 60.)



[After Sieberg.

FIG. 41.—NORMAL FAULT, DEVELOPED FOLLOWING BENDING OF STRATUM.

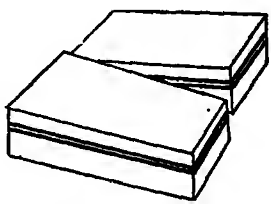


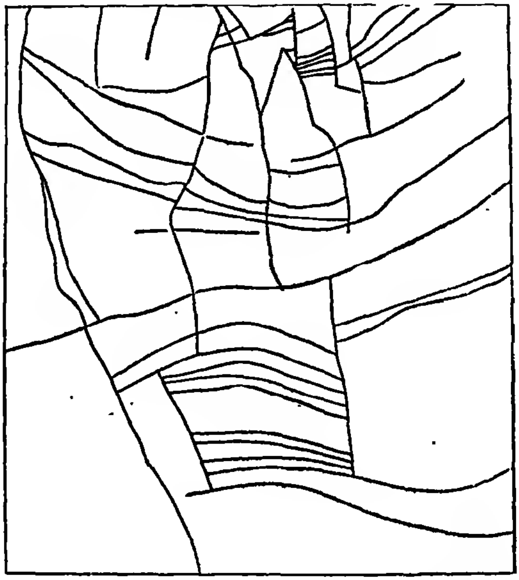
FIG. 42.—NORMAL FAULT, SHOWING VARIATION IN THROW.

Faults occur not only singly but also as members of a related system of fractures (Fig. 43). They may branch or, alternatively, one large dislocation may be replaced by a number of smaller faults of parallel trend. We may find a number of parallel faults throwing down in the same direction, giving "step-faulting," or pairs of faults with opposed throws giving a horst (Fig. 44), or a rift (Fig. 45) (German. *Graben*).

The geometrical and geological characteristics of faults are an important factor in coal-mining operations ; normal

[1] In "tear-faults" horizontal is predominant over vertical movement, but such faults commonly occur in association with thrusts in regions of compression.

faulting is very common in the British coalfields, and it was in the development of coal-mining that our earlier



[After Spurr.

FIG. 43.—FAULT-PATTERN IN ASPEN DISTRICT, COLORADO. 1 inch=4,500 ft. approx.

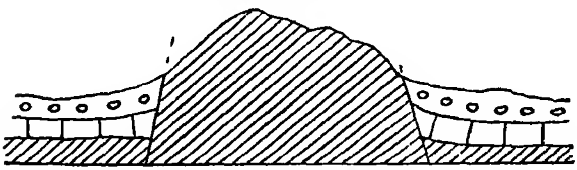


FIG. 44.—A HORST.

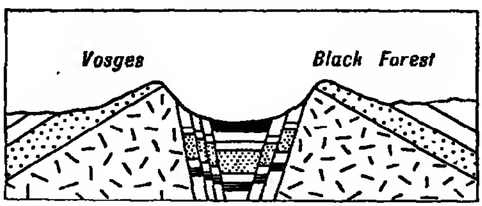


FIG. 45.—THE RHINE RIFT (SIMPLIFIED).

knowledge of faults was obtained. It is particularly important to note, for instance, that as the fault-plane

generally departs from the vertical, sometimes markedly, there is an area of "dead-ground" in which a coal-seam or other stratum will *not* be encountered (Fig. 46). Again, it is clearly vital to have means of determining, at the faulted termination of a seam, whether its continuation is to be looked for above or below, *i.e.* the direction of the "throw" of the fault. This is simple if the geology of the district is thoroughly known, but in other cases may present considerable difficulty. To the geographer, however, one of the most significant aspects of faulting is its expression in relief, and to this subject we may now turn.

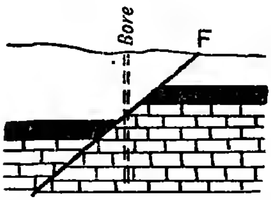


FIG. 46.—NORMAL FAULT, SHOWING "DEAD GROUND" WHERE COAL SEAM IS ABSENT.

Original and secondary fault-topography.—It is apparent that immediately after a faulting movement is complete, a surface feature or "fault-scarp" must mark its course. Such a feature, however, is temporary, disappearing in the course of erosion. In western North America there are many excellent examples of veritable fault-scarps in which the movement has been so recent that erosion has only modified the original form. This is particularly true of the arid and semi-arid regions in which atmospheric waste is slow. But it must be clearly realized that, throughout Britain and Western Europe and, indeed, over the greater part of the land areas the existing land surface is hundreds, or even thousands, of feet below the surface upon which the original fault-scarp was formed. Any irregularity which occurs at the line of the fault is thus a secondary feature developed during erosion. In areas of soft rocks a fault may make no feature, although it may mark the common boundary of contrasted soil and vegetation regions. Where, however, rocks of differing resistance are brought together an inequality of surface must normally result. Such features have been termed *fault-line scarps* by W. M. Davis to distinguish them from the original steps or *fault-scarps*. If at the level of the present erosion surface the softer rock is on the downthrow side, this side will form lower ground and the fault-line scarp will imitate the original fault-scarp in its form. It is termed a *resequent* fault-line scarp (Fig. 47). If, however, the harder rock is on the downthrow side, the

drop in surface level will be in the reverse direction to the throw of the fault and the scarp is termed *obsequent* (Fig. 47). Similar relations exist between faults and valley-lines. A valley may follow, or be coincident with, an original fault-formed depression, or it may be "fault-guided," erosion having taken advantage of the band of shattered rock, or the juxtaposition of hard and soft rocks, to make a valley along the fault-line. Bearing in mind this important distinction between original and secondary fault-topography we may briefly examine some notable examples of faulting in relation to relief.

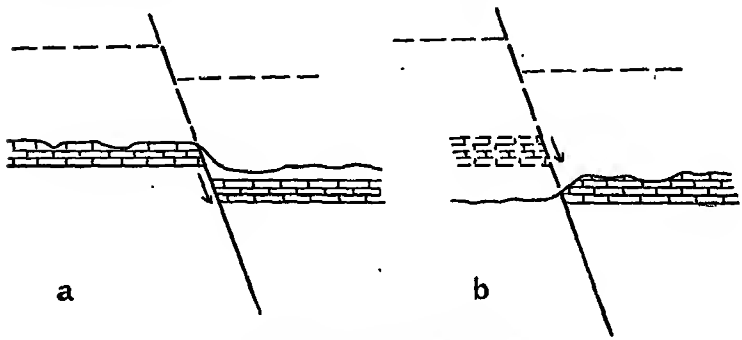


FIG. 47.—FAULT-LINE SCARPS.

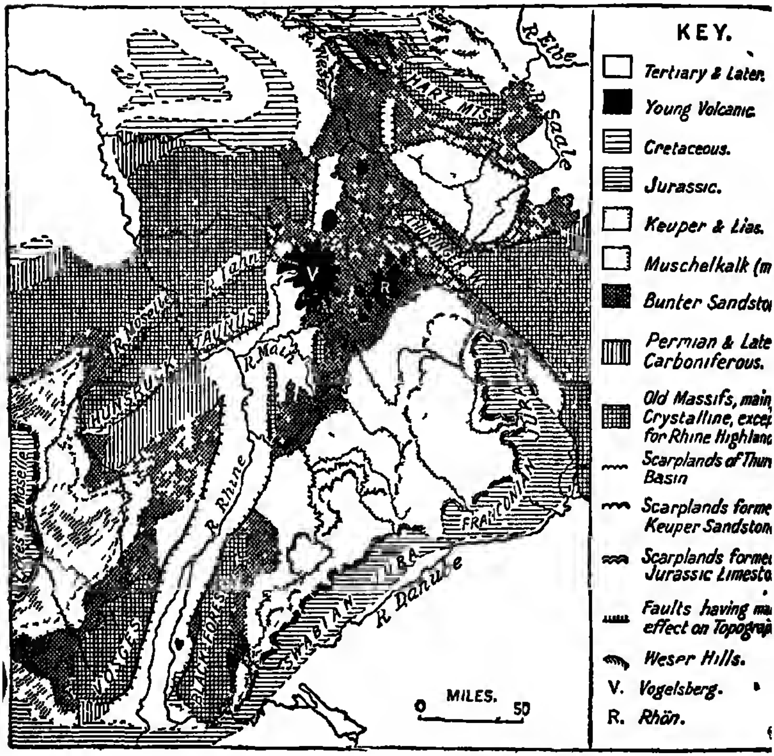
(*a*) Resequent. (*b*) Obsequent.

Rift valleys.—The rift valley in which a block of country has been dropped between parallel faults is a common relief-feature. An admirable example is afforded by the Rhine rift, whose features are illustrated in Figs. 45 and 48. Here the flat floor of the rift, 20 miles wide and 200 miles long, represents the upper surface of a down-dropped crust-block covered by later deposits. The rift is an original depression, partially filled with the deposits of late Tertiary seas which extended along it, together with later glacial deposits and the alluvia of the Rhine. More than one fault occurs on each side of the rift, the structure being complex in detail, though simple in outline.

An even more impressive series of rift valleys extends from the Taurus Mountains in Asia Minor into South Africa. Amongst the rifts of this series are the central valley of Syria, the Gulfs of Suez and Akaba, the Red Sea and the Gulf of Aden. In East Africa there are several

parallel belts of rifting extending from north to south, in which lie most of the great lakes of the region (Fig. 49). This immense belt of faulting persists over a north–south distance of nearly 2,000 miles and passes indifferently through rocks of all characters.

The Midland Valley of Scotland, which is often cited as a rift valley, can hardly lay claim to that title in the same



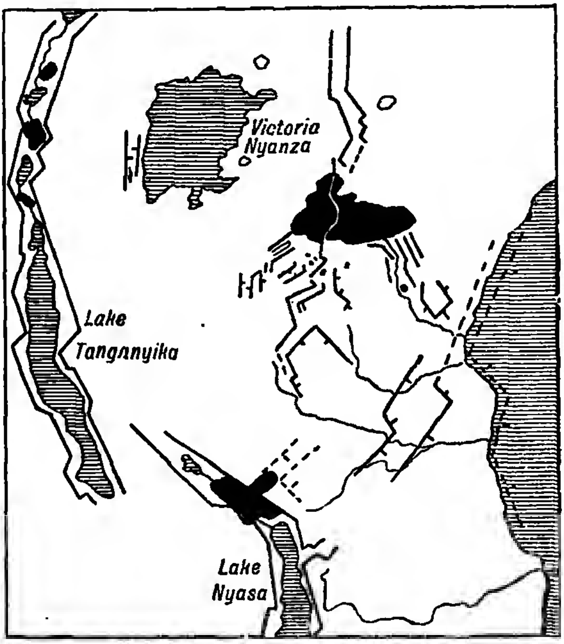
[From Shackleton's "Europe," Longmans, Green

FIG 48.—THE RHINE RIFT VALLEY.

sense as the Rhine and African rifts. In the last two the relief is largely "original," though modified by erosion and infilling. The Scottish Lowland is fault-bounded, but its history and present surface form are much more complex. It is far from certain that the Highland boundary fault and its counterpart along the edge of the Southern Uplands are simple normal faults; moreover, the low-lying intervening tract owes its character to river

erosion and glaciation to a very high degree. A true rift-valley may have existed on this site in the past, but the present land forms are entirely "secondary," in the sense defined above.

The exact mechanics of rift-valley formation has given rise to some controversy. It is clear that a wedge-shaped block cannot subside in a wedge-shaped cavity of the same size, and that therefore more is required than the formation of two parallel faults, inclined towards each



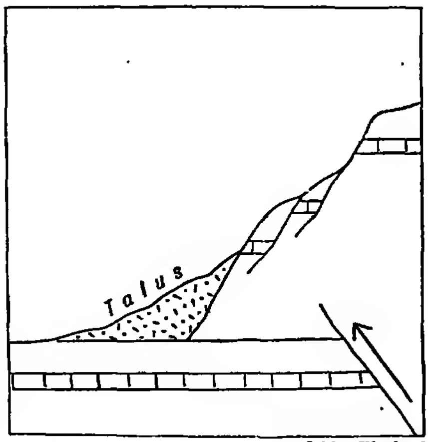
[After Meyer.

FIG. 49.—THE EAST AFRICAN RIFTS.
Lava-flows in black.

other. The dropped-block arrangement might arise, it is true, if the faults formed not simultaneously but successively, but this would not produce a symmetrical structure such as the Rhine Graben. Certain students of the East African rifts have sought to demonstrate that the faults are "thrust-faults" diverging downward in depth; in which case there would be no difficulty about the subsidence of the central block (Fig. 50). Initially such thrust-faulting might produce overhanging fault-scarps, but it has been contended that secondary slip-

faulting, coupled with weathering, would destroy this appearance (Fig. 51). Such a view would make rift-faulting essentially a compressional phenomenon. In further support of this idea it has been pointed out that the bounding blocks often dip away from the rift (cf. Fig. 45), suggesting that the latter has formed on the crest of an anticline—the "dropped keystone of the arch." While these views have enjoyed distinguished and competent advocacy, the majority of observers now favour a purely tensional origin. The bounding fractures certainly appear to be *normal* faults in most cases and the necessary space for subsidence is believed to be provided by a literal pulling apart of the two sides. Under such conditions the dropped block would not exactly fit the available space and marginal fissures would be formed. The existence of such fissures can be demonstrated in many actual rift-valleys; minor troughs often occur at the foot of the main fault-scarps and emission of lava is a characteristic feature, pointing to the existence of gaping spaces below ground which have acted as channels for its uprise. In further support of the tensional theory we may call attention, following Taber, to the closely similar behaviour of a rifted block of wood floating in water. The central portion drops and the marginal blocks are tilted into a pseudo-anticlinal arrangement (Fig. 52). We may perhaps see in this analogy a suggestion that the faulted blocks of the crust are in a similar flotation relation to the underlying sima.

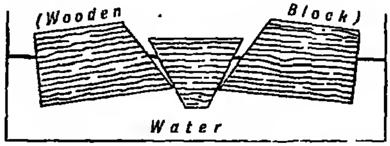
FIG. 50.—THRUST-FAULTS BOUNDING A RIFT-LIKE STRUCTURE AND DIVERGING IN DEPTH.



[After Wayland.

FIG. 51.—EDGE OF RIFT-VALLEY, INTERPRETED AS DUE TO UPTHRUST, FOLLOWED BY MINOR SLIP-FAULTING.

Block-mountains.—The great rift valleys of the Rhine and East Africa occur in regions which show other evidence of tension, but they are the dominating features of these regions. We may pass to consider cases in which more extensive foundering has occurred, producing large numbers of tilted earth-blocks. The classic example of such



[After Taber.

FIG. 52.—EXPERIMENTAL IMITATION OF RIFT-STRUCTURE.

"block-faulting" occurs in the Great Basin, between the ranges of the Sierra Nevada and the Wasatch Mountains in the Western United States. In this region we find not only typical rift valleys but also asymmetrical fault-valleys, bounded by a fault-scarp on one side and the back-slope of a tilted block on the other. To this type of structure as a whole the term "basin-range structure" has been applied. The mountains with their fault-scarp faces are true "block mountains" and to such the name should be restricted.[1]

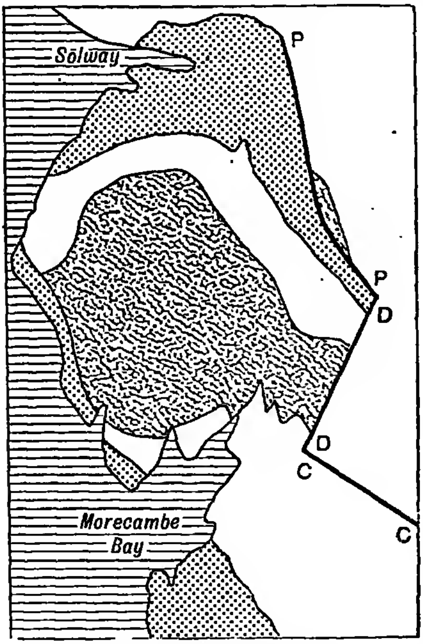


FIG. 53.—BLOCK STRUCTURE IN THE NORTHERN PENNINES.

P–P, Pennine Fault; D–D, Dent Fault; C–C, Craven Fault.
Older rocks of Lake District=irregular stipple; Carboniferous rocks=white; New Red Sandstone=dotted.

The asymmetrical fault-valleys and block mountains of Western North America present us with a largely *original* relief, though erosion has softened the asperities of profile and partially filled in the valley bottoms with waste.

[1] Some authors speak of the ancient upland massifs of Europe as "block-mountains," but such a use is to be deprecated, for though faulting enters into their structure not a little, they are not analogous to the true block-mountains described above. "Upland massif" is a sufficient description of them.

Similar structures of older date and with *secondary*, or *revived*, relief-forms characterize other regions. Thus in the Northern Pennines we have a well-developed block structure, in which, however, tilting is subordinate. The Eden Valley is bounded on its eastern side by the great Pennine fault. It was later filled by the New Red Sandstone deposits which have since been partially

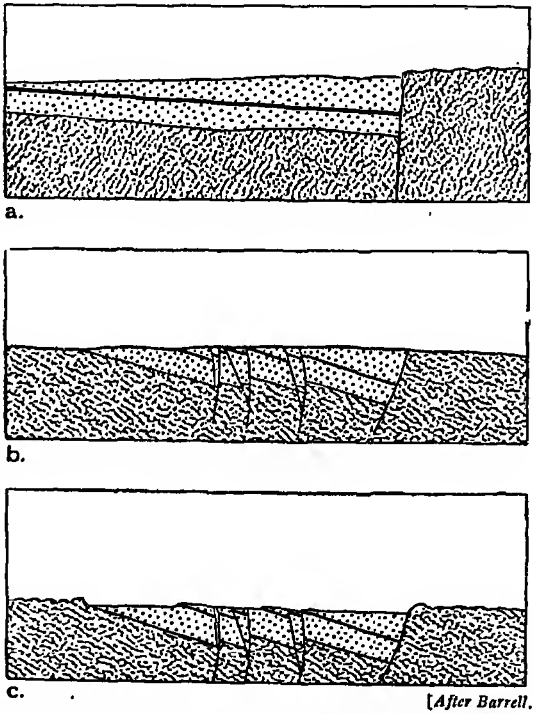


Fig. 54.—The Evolution of the Connecticut Valley.

(*a*) Subsidence along main fracture; filling of trough with red sandstones and lava-flows (black). (*b*) Block-faulting followed by erosion. (*c*) Dissection of area following renewed uplift.

removed by river action and glaciation (Fig. 53). The Vale of Clwyd in North Wales is a somewhat similar pre-Triassic valley, partially exhumed from beneath its infilling. An even more striking example is afforded by the region of the Connecticut Valley. The region subsided along a fracture on its eastern side in Triassic times, but became filled with a great thickness of the red desert sands

of that period, together with lava which flooded the basin at intervals (Fig. 54). Later, block-faulting took place, but its effects on contemporary relief can only be surmised, as it was followed by a protracted period of erosion which levelled the whole tract (Fig. 54). Later again, uplift of the region as a whole led to river-dissection and this was followed by glaciation. To-day, the old fault-trough figures as a tract of lowland, lying between the Western and Eastern Highlands of older rocks, still preserving a large part of its Triassic infilling (Fig. 54). It is bounded on the east by a fault-line scarp, following the original

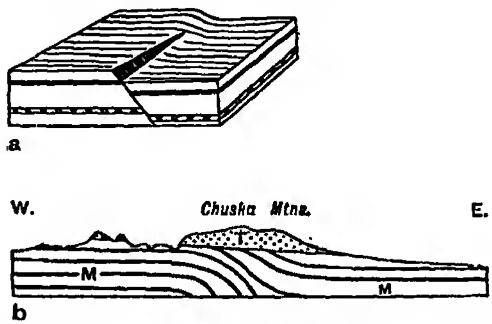


FIG. 55.—MONOCLINES.

(*a*) Monocline passing into normal fault. (*b*) Eroded monocline in Mesozoic rocks (M), covered by Tertiary sandstone (T).

fracture-line, and is diversified by the asymmetrical ridges formed by the faulted lava sheets.

Monoclines.—Folding, like reversed faulting, represents a contraction of area under compression and is thus naturally absent or subordinate in regions of tension, but to this statement an exception must be made in favour of the folds known as monoclines. These flexures exhibit only one inclined limb, which links tracts of horizontal strata at different levels[1] (Fig. 55). Monoclines are evidently closely related in origin and effects to normal faults, into which, indeed, they frequently pass (Fig. 55).

[1] The reader is reminded that the term "monocline" should not be extended to cover asymmetrical anticlines such as that of the Isle of Wight, which are not tensional features (cf. p. 66).

CHAPTER VIII

VULCANICITY AND EARTH-MOVEMENT

Introductory.—The term "vulcanicity" covers all those processes in which molten rock material or *magma* rises into the crust, or is poured out on its surface, there to solidify as a crystalline or semi-crystalline rock. The name suggests a connexion with volcanoes, but it is well to emphasize that volcanic (or extrusive) rocks, erupted at the surface, are hardly more important than intrusive rocks, injected into the crust and subsequently laid bare by erosion. Moreover, the greater bulk of the volcanic rocks of the earth's surface were not erupted from volcanoes in the narrow or traditional sense, but represent upwelling from fissures. Thus the connotation of the term vulcanicity is wide.

We have noted (p. 9) that the outflow of molten rock material was formerly taken to imply a liquid core below the surface of the earth. The facts which render this hypothesis untenable leave unaffected the plain facts that emissions of magma do take place, and that the temperature of their regions of origin must be high. We have also noted (p. 10) the probability that it is pressure which normally maintains the sub-crustal regions in an effectively solid state, and hence it is easy to see how earth-movement, by a temporary and local relaxation of pressure, may lead to melting. A mass of molten rock, once in existence, may be squeezed through the rocks of the crust by earth-pressures much as water is squeezed out of a sponge. In some cases it makes its way along the natural planes of parting provided by joints, faults, and bedding planes; or it may rise along actual open fissures. In other cases it seems to have made its way by melting and incorporating the overlying rocks of the crust.

Bathyliths.—A very cursory view of the distribution of igneous rocks is sufficient to demonstrate their close relation in time and space with earth-movement. Let us consider first the case of the larger bodies of intrusive rock. These are the so-called bathyliths, very commonly, though not invariably, formed of granite. They are large dome-shaped masses whose sides plunge steeply to unknown

[Photo by H.M. Geol. Survey. Crown copyright reserved.

FIG. 56.—SILL SHOWING COLUMNAR JOINTING, DRUMADOON, ARRAN.

[Photo by H.M. Geol. Survey. Crown copyright reserved.

FIG. 57.—ARTHUR'S SEAT AND SALISBURY CRAGS FROM BLACKFORD HILL, EDINBURGH.

Complex denuded volcanic vent of Arthur's Seat on right, with sill of Salisbury Crags forming escarpment on left (p. 110).

depths; their base is never seen. Good examples are afforded by the great granite mass of Wicklow and the granite intrusions of Montana. As regards their mode of emplacement some differences of opinion exist but the view is gaining ground that they rise by wedging off large numbers of blocks of the surrounding country rock, which sink and are melted and incorporated. Smaller masses of similar dome-shaped form are called " stocks " or " bosses." Bathyliths are characteristic of the heart regions of mountain ranges, appearing at the surface only after prolonged denudation. Their longer axis generally lies parallel with the axis of the range and its constituent folds;

[*After Daly.*

FIG. 58.—BATHYLITHS IN BRITTANY.
The lines mark the chief axes of folding.

and they thus contribute to the pronounced structural graining of denuded mountain tracts. Thus in the north-west massif of France (Fig. 58) we see innumerable large masses of granite which were intruded during the Armorican orogenesis. They are elongated generally from east to west, thus bringing out the trend lines of the old mountain system ; and, as a rule, they form ridges of high ground between the softer and lower-lying slate belts. Similarly, the granite bathyliths of the Grampians and the great Dublin mass mark the line of the Caledonian folds.

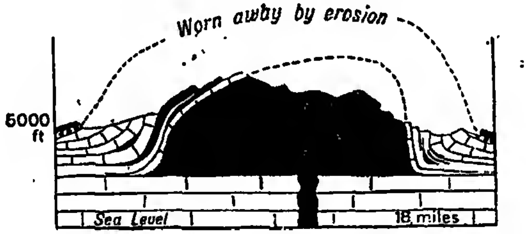
Phacolites and laccolites.—A simpler and more direct relation between intrusive masses and folding is seen in the case of the bodies called phacolites and laccolites.

They are generally smaller than bathyliths, though they may attain a size sufficient to render them important elements in landscape. Their relation to the surrounding rocks is entirely different from that seen in the larger bathyliths. Phacolites are lens-shaped masses of rock occupying the saddles of anticlines or the keels of synclines, places where rigid rock sheets naturally gape apart in the folding process (Fig. 59). Laccolites, first described from the Henry Mountains in Utah, are in the nature of huge blisters, in which the covering sedimentary rocks have been thrown into a dome by the local accumulation of molten rock beneath them. They may be conceived as filled by a "pipe" from below, though this has rarely,

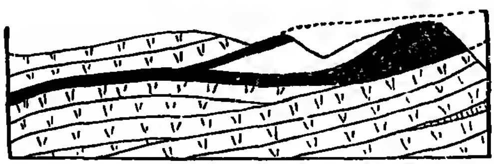
[After Harker

FIG. 59.—THE CORNDON PHACOLITE.

Igneous rocks (black) in folded Ordovician sediments.



[After Gilbert.



[After H.M. Geol. Survey.

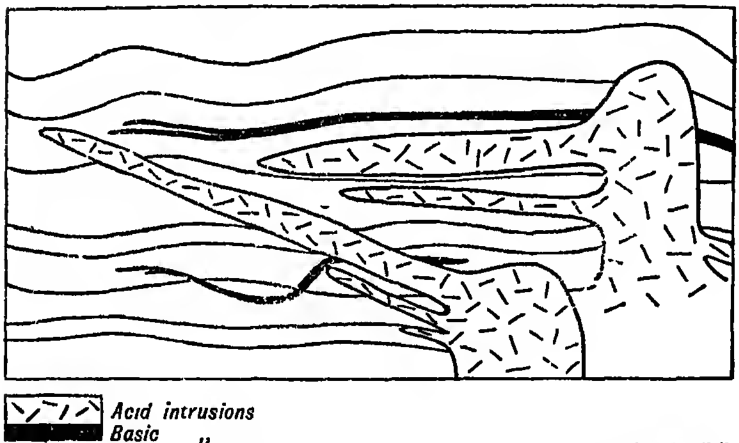
FIG. 60.—LACCOLITES.

Above, Mount Hilliers, Henry Mountains. *Below*, composite laccolite in Skye, intruded into basalts. Basic rocks=black; acid rocks=white.

if ever, been seen, or laterally along the bedding planes of the surrounding sediments (Fig. 60). As usually interpreted, the intrusion of the molten material is taken as the active cause of the up-arching, but it is quite likely that in some cases at least the reverse is the case, the magma being "sucked in" as an incident of earth-movement.

Such would certainly seem to be the case with phacolites. Both before and after the breaching of the sedimentary cover by erosion, laccolites tend to form striking isolated conical hills. A beautiful example is afforded by the Traprain Law in Haddingtonshire as well as by those of the Henry Mountains (Fig. 68).

Sills.—Laccolites are closely related in manner of origin to the stratiform intrusions of igneous rock, aptly termed "sills," which may vary in thickness from a few inches to hundreds of feet. These represent injections of magma between the bedding planes of sedimentary rocks, though they may break across the bedding and change their "level" at intervals. They are often horizontal offshoots



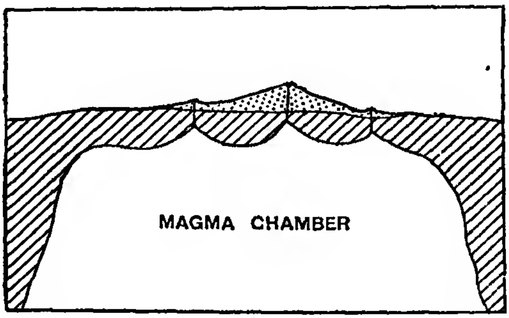
[After Cox and Wells.

FIG 61.—BOSSES AND SILLS IN THE CADER IDRIS DISTRICT.

from laccolitic or boss-like bodies, as is illustrated in some examples from North Wales (Fig. 61). When tilted and exposed by erosion they form salient elements in landscape, forming precipitous scarps, as in the case of Salisbury Crags, overlooking the City of Edinburgh (Fig. 57), or that of Cader Idris, where the scarp face of a sill, 1,000 feet thick, overlooks the low ground along the Barmouth Estuary. In the Karroo region of South Africa horizontal sills form the capping of those peculiar mountains which have the form of a truncated cone.

Volcanoes.—The outflow of molten rock as lava at the surface of the earth, taken in conjunction with the marked explosive violence of some of the eruptions, would seem

to imply some extra eruptive force inherent in the magma, undoubtedly provided by the included gases, and especially by steam. Under the great pressures ruling in depth, the abundant water included in all magmas may be maintained in a liquid condition, but with release of pressure a point is reached at which it flashes into steam and exerts enormous expansive force. Such at least is the mechanism of geysers and there is little doubt that a similar process provides the effective means of many volcanic eruptions. The rising lava is often caused to froth by the expanding included gases, just as carbonated mineral waters froth when the cork is removed from the bottle and, in both cases, a bodily raising of the liquid can be brought about by this means. It must of course be assumed that volcanoes are connected underground



[After Daly.

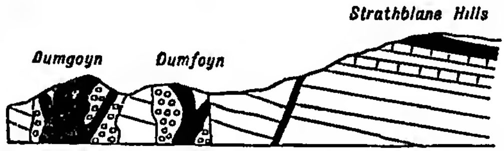
FIG. 62.—INFERRED RELATIONS OF VOLCANOES TO UNDERLYING MAGNA CHAMBER.

with bathyliths or some kindred type of magma reservoir as is illustrated in Fig. 62.

In the building of an ordinary volcanic cone the initial episode is the blowing of a hole through the overlying crust. This may become partially choked with fragments of the disrupted country rock, but it normally serves as a conduit for the rising magma, part of which solidifies as a plug of roughly cylindrical shape filling the pipe or neck of the volcano (Fig. 63). The lower portions of the cone will normally consist of an accumulation of coarse blocks of country rock blown from the orifice—an *agglomerate*. Thereafter, there may be a succession of flows of lava, punctuated by renewed explosions, giving interstratified beds of *ash* or *tuff* in which lava fragments mingle with those of the country rock.

The varying form and extent of volcanic cones is found to be very directly dependent upon the fluidity of the lava involved. With lavas of fluid type, ready and unchecked flow takes place, and explosive activity, with its resultant beds of tuff and agglomerate and large explosion craters, is subordinate. With lavas of more viscous character the choking of the vent by solidification of the plug occurs more frequently; and this leads to recurrent explosions and the production of vast quantities of dust and tuff which may equal, or exceed, the actual lava in bulk.

The fluidity of lava depends upon its composition. Dark-coloured lavas of the basalt type, which are poor in silica and rich in iron and magnesium, are naturally very fluid. Lavas of low density, rich in silica and poor in iron- and magnesium-bearing minerals, are rendered effectively fluid only by their content of gases. The loss of these gases on eruption leads to rapid congealing and



[After Geikie.

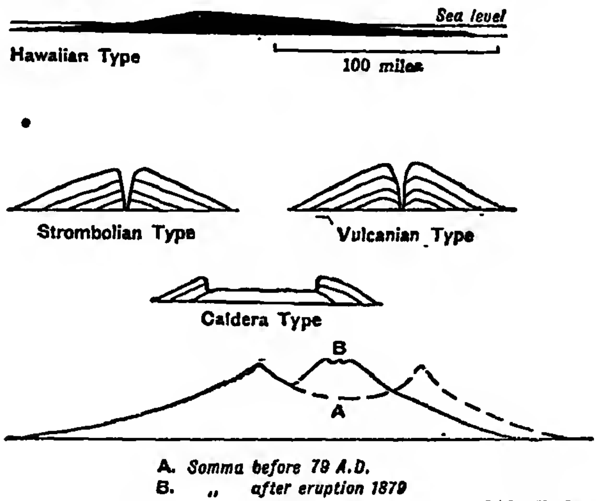
FIG 63.—VOLCANIC NECKS, STIRLINGSHIRE
Denuded remnants of the feeding pipes of ancient volcanoes.

solidification. Hence, it naturally results that the heavier basic lavas build flat cones of large extent typified by the gigantic lava piles of the Hawaiian Islands. Mauna Loa, one of the great volcanoes of this group, has a height reckoned from sea-bottom of 30,000 feet and a diameter at this level of more than 100 miles (Fig. 64). At the other extreme are the curious little lava mounds, termed "puys," which diversify the volcanic areas of the Auvergne and represent the accumulation of stiff pasty acid lavas immediately round the vent. The eruptions of Mt. Pelée in Martinique in 1902–1903 possessed rather similar features. The lava was too viscous to flow and was protruded from the vent in the form of a pillar or spine, which rose to a height of 700 feet or more above the summit of the cone.

Extreme explosive violence, probably associated with a notably non-fluid lava, was manifested in the eruption of Krakatoa in the Straits of Sunda in 1883. No lava

was emitted, but a terrific explosion completely destroyed the small island of Krakatoa, producing enormous quantities of volcanic dust.

The classic volcanoes of the Mediterranean region, which coloured earlier notions of vulcanicity to so large an extent, are intermediate in character between the extreme types we have noted. The lavas of Stromboli are of relatively fluid type and its cone is largely a lava-cone, though some explosive activity is represented by beds of tuff. In the eruptions of Vulcano in 1889 the lava was more viscous and explosion played a larger part. In such



[After Harker.

FIG. 64.—TYPES OF VOLCANIC CONE.

cases the crater is much larger, having a funnel-rather than a pipe-like form (Fig. 64). It is in cones of this type that a later explosion sometimes destroys a large part of the cone, producing a large shallow flat-floored crater or " caldera " (Fig. 64).

Fissure eruptions.—All the forms of eruption so far noted are of the central type, proceeding from a single vent or a group of related vents. Though these are the traditional volcanoes of picture and story they are less important in their bulk effects, and less significant as factors in terrestrial relief, than the great fissure eruptions. In these there is little or no explosive activity and a correspondingly small amount of tuff. The lava wells up

quietly along numerous parallel fissures and floods large areas of country, while the successive flows may accumulate to a total thickness of hundreds of feet. The " Columbia " lavas of Washington and Oregon are estimated to cover an area of 250,000 square miles and to attain a thickness of over 4,000 feet. Geikie graphically described this region in the following terms : " We had been riding for two days over fields of basalt, level as lake-bottoms. . . . It was as if the great plain had been filled with molten rock which had kept its level and wound in and out along the bays and promontories of the mountain slopes as a sheet of water would have done." Other examples are afforded by the " Deccan Traps " of North-west India, whose extent is indicated in Fig. 65; and the lavas of Antrim, the Western Isles of Scotland, Iceland, and Greenland, which are remnants of a great lava-field of which parts have become submerged. It is clear that in such eruptions we see the extreme expression of the tendency to widespread flooding illustrated in the Hawaiian cones. The lavas erupted under these conditions are dominantly basalts and their extremely uniform composition suggests that the flows proceed direct from the underlying sima, with little hindrance or contamination *en route*.

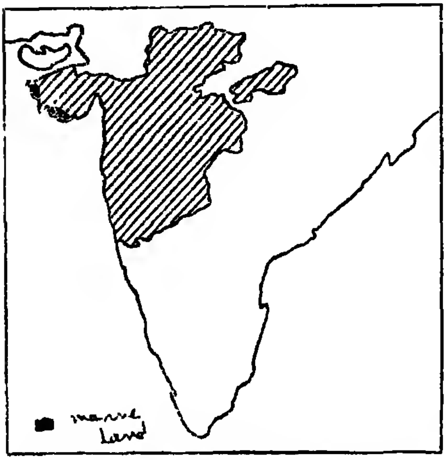
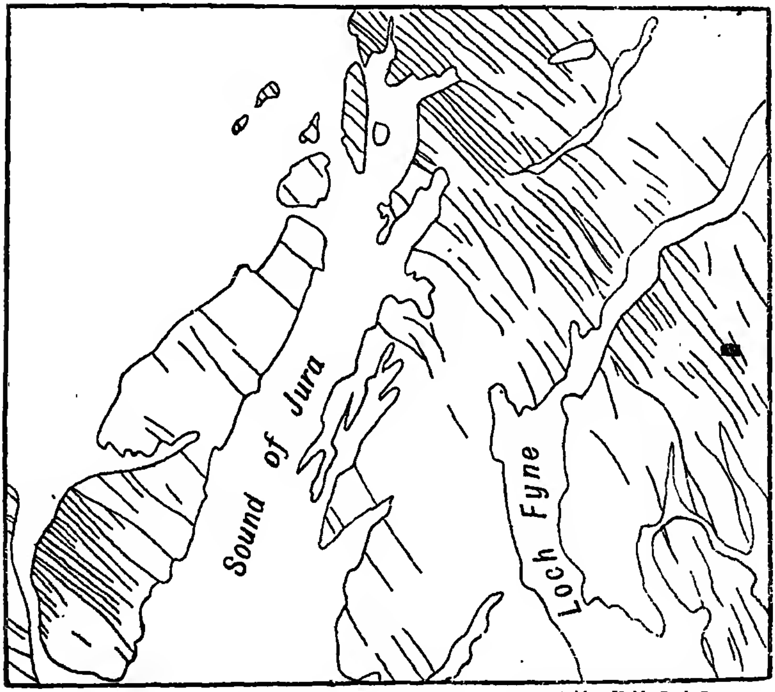


FIG. 65.—THE " DECCAN TRAP " REGION OF INDIA.

Dykes.—The feeding fissures which retain a filling of solidified magma are known as dykes, and though they are often hidden by the overlying flows, in other cases denudation has laid them bare. They form veritable systems or dyke-swarms, maintaining a parallel direction over wide areas of country and being, in some cases, so numerous that it is almost impossible to represent them all, even upon a map of large scale. A portion of the great dyke-swarm associated with the Tertiary fissure eruptions of Western

Scotland is shown in Fig. 66. It should be noted that dykes also occur in association with central volcanoes, where they radiate from the central focus. In such cases they are generally less numerous and traceable for shorter distances. Dykes figure variously in relief according to the relative hardness of the dyke rock itself and the surrounding country rocks. Where the dyke rock is



[After H.M. Geol. Survey.

FIG. 66.—A PORTION OF THE "DYKE-SWARM" OF W. SCOTLAND.

relatively hard it may weather to form a wall-like mass clearly traceable across country. This is well illustrated by the famous Cleveland dyke, which traverses the moors of North-east Yorkshire. In other cases it may "weather in," forming a depression or gully. Dykes are especially prominent on coastlines, where they determine the position of small promontories, clefts, and caves (Fig. 67).

The Tertiary Igneous Activity in N.-W. Britain

The Tertiary igneous rocks of Western Scotland are so

admirably exposed for study and have been the subject of so much careful observation that we conclude our account by a brief summary of this igneous cycle as a whole. It is particularly notable that although the bulk of the rocks cannot be older than Early Tertiary (Eocene), erosion, following a certain amount of faulting, has bitten sufficiently deeply to expose the plutonic "roots" in some cases, as well as to render visible vast thicknesses of lava flows. As in many similar areas, three phases of the igneous cycle may be distinguished: first, the volcanic phase, the eruption of lavas; secondly, the plutonic phase, when major intrusions were injected locally; and finally, the phase of minor intrusions. A certain amount of overlapping and alternation between these phases is not precluded by the suggested scheme. Further, there are two "modes" of vulcanicity within the area, regional and local. The regional eruptions, of the fissure type, form part of those of a much larger province extending as far as Iceland, Greenland, and Spitzbergen. More than sixty years ago J. W. Judd inferred the presence of local or "central" volcanoes in the Hebrides, but his views were opposed by Archibald Geikie and others, who attributed all the lavas to fissure eruptions. More recent work, however, has vindicated Judd's views. Though a large part of the lavas no doubt represent fissure-eruptions, local centres of eruption have been demonstrated in St. Kilda, Skye, Rum, Mull, Arran, and Ardnamurchan, associated in all cases with considerable intrusive masses.

The sequence of events in broad terms was as follows: First, came the eruption of the regional lava flows, fed by fissures trending north-west to south-east. Vast thicknesses of lava accumulated, and as now exposed on the Hebridean hillsides they show a characteristic terraced profile, due to the ready weathering of the slaggy and vesicular tops of the successive flows. The lavas were poured out on land with sufficient intermissions to permit the rotting of exposed lava-surfaces and the local accumulation of lacustrine or river-borne sediment, preserved beneath overlying flows. Next, we find evidence of the first eruptions of the "central" volcanoes, which had a long life and passed through several phases. The first stage is commonly marked by thick accumulations of agglomerate, *i.e.* accumulations of fragments of country rock and earlier lavas, produced by great explosions.

[*Photo by H.M. Geol. Survey. Crown copyright reserved.*

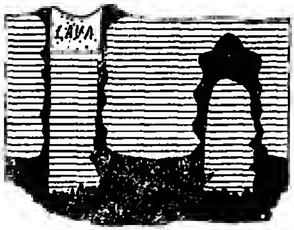
FIG. 67.—A BASIC DYKE OF TERTIARY AGE.
Cutting Triassic sandstone, Arran.

[*Photo by H.M. Geol. Survey. Crown copyright reserved.*

FIG. 68.—TRAPRAIN LAW, HADDINGTON. A SMALL LACCOLITE (p. 110).

But later the Mull Volcano must have been of Hawaiian type, building an extensive cone of basic lavas.

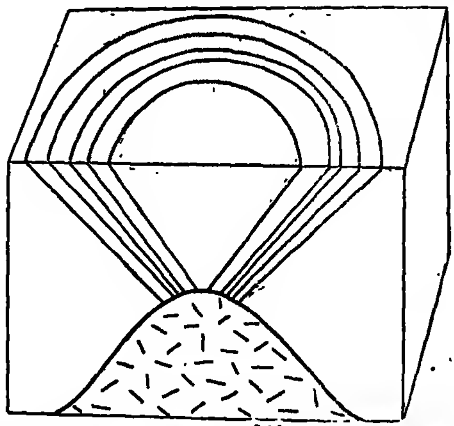
It is in the regions beneath the central volcanoes that the major intrusive masses were emplaced. They comprise both basic rocks such as built the Cuillin Hills of Skye, and granites, as in the Red Hills. These intrusions appear to be of "normal" laccolithic form, but the recent survey of Mull has revealed different relations. Here the intrusive masses occupy arcuate or cylindrical fissures, and appear to have risen incidentally to the subsidence of cylindrical blocks of the crust. Similar relations were earlier discovered among the Palæozoic (Old Red Sandstone) igneous rocks of Argyle. In both localities the intrusions take the form of "ring-dykes" or "ring-bosses," while, if the cylindrical collapse penetrated to the surface, "cauldron-subsidences" occupied by lavas were formed. Idealized structures of this type are shown in Fig. 69.



[*After H.M. Geol. Survey.*

FIG. 69.—RING-DYKES, RING-BOSS, AND CAULDRON-SUBSIDENCE.

The phase of minor intrusions witnessed the widespread injection of north-west to south-east dykes and of sills. It should be noted that the former cut the lava flows and cannot therefore be regarded as their feeders. They seem to mark the continuance or resumption of regional tension and the dyke-swarm extends as far as the North and Midlands of England and North Wales. It should be noted that the north-west to south-east direction is that favoured by Tertiary faults in Britain, so that we have confirmatory evidence of a pronounced extension at right-angles to this direction. The regional dykes cluster, *i.e.* are



[*After H.M. Geol. Survey.*

FIG. 70.—CONE-SHEETS, SHOWING INFERRED RELATION TO MAJOR INTRUSION.

more numerous, in the vicinity of the plutonic complexes. On the south-east coast of Mull 375 dykes of aggregate thickness 2,504 feet were counted in a distance of 12·5 miles, indicating thus a crustal stretching of 1 in 26·4. It was pointed out by J. W. Evans that the "Biscayan deep" trends north-westwards from the Bay of Biscay parallel with the Tertiary dykes and faults, and the extension was interpreted by him as the result of a crustal drift towards this deep.

Amongst the minor intrusions there are also local groups, evidently related to the volcanic foci. Thus there are dykes which follow radial directions, as well as tangential and ring-dykes. More remarkable are the cone-sheets which surround the volcanic foci. They are very numerous, being separated by only thin screens of country-rock, and are inclined inwards at about 45° (Fig. 70). A. K. Wells succinctly summarizes the origin and relations of ring-dykes and cone-sheets in saying that both "develop above the nose of an advancing bullet-shaped plug of magma" (Fig. 70). The two types clearly reflect different stress conditions, however, and much more remains to be discovered as to their significance.

Leaving aside the rich harvest of petrological interest presented, the "basal wrecks" of the Mull and Ardnamurchan volcanoes are for the geomorphologist striking examples of the dissection of volcanic "interiors," and not the least striking features of these rugged landscapes are the concentric lineaments of fractures and intrusions faithfully etched out by erosion around the old eruptive centres.

CHAPTER IX

THE ORIGIN OF THE FORCES RESPONSIBLE FOR EARTH-MOVEMENT

WE noted on p. 62 that any fundamental treatment of earth-movement involves some discussion of the origin of the forces involved. On this subject there has been much controversy, and no finality of opinion has been reached.

The thermal contraction theory of mountain formation.—The most familiar and in some respects the most generally acceptable theory of mountain building involves the accommodation of the cooled and solidified lithosphere to a still shrinking nucleus. In its simple qualitative form this theory dates back to Newton, and is readily, perhaps too readily, comprehended. It cannot be accepted or rejected in the light of the mere analogy of the wrinkled skin of a shrunken apple, but must be related to the thermal state and history of the earth, so far as these are known, and to the effects it is required to bring about.

The earlier quantitative estimates of the contraction due to cooling were invalidated by the failure to allow for radio-active heat. Jeffreys has, however, re-stated the hypothesis in accordance with his interpretation of the earth's cooling history, and his treatment has done much to restore it to favour. We have already noted (p. 21) that his calculations indicate that no appreciable cooling can have taken place in the central regions since the solidification of the crust. In regard to the outer parts of the earth, however, each shell cools more than the one below it in a given interval of time, and hence attempts to contract. Its contraction is obstructed by the hotter matter below, which is contracting less. Hence it can only actually achieve contraction by spreading out and becoming thinner. The completely solidified outer portion can undergo no further cooling and contraction and thus it inevitably becomes too big to fit the inner contracting shells. In this way a state of stress will be set up in the lithosphere, tending to folding and faulting, or, in the general view, crustal shortening. In the picture so presented the surface layers are in a state of compression

while the weak shells below are subject to tension. Between them there must be a " level of no strain," in which the amount of contraction is just sufficient to permit accommodation to the shrinking nucleus. Starting at the surface of the earth this " level of no strain " must have moved inwards as cooling progressed.

Up to a point this theory gives a very satisfactory explanation of mountain building. In testing it against the facts of earth structure the first question is clearly the amount of compression which it allows. It should be noted that it is not only simple contraction by cooling that is available, for glassy rocks may also contract in crystallization, and further contraction ensues upon the loss of included gases and water. Jeffreys' calculations indicate an average cooling of about 500° C. in the outer 400 km. of the earth, and this would be equivalent to a reduction of 20 km. in radius or 130 km. in circumference. A further allowance for crystallization-contraction and loss of gases, etc., may be made, giving, it is thought, a maximum reduction in circumference of 200 km., or in area of 5×10^{16} sq. cm. It is clearly a very difficult matter to evaluate from studies of geological structure the amount of crustal shortening which has actually taken place. Many existing ranges are inadequately known and many have suffered virtual obliteration by erosion. By adding estimates of the " shortening " recorded for the chief existing ranges Jeffreys arrived at an areal compression of 2×10^{16} sq. cm. This is less than half the calculated available compression ; but it is certainly an underestimate, and possibly a serious underestimate, since it cannot include the older episodes of mountain making. Moreover, there has been a tendency in recent years to claim greater shortening in the existing major ranges, and if these claims are well founded, a serious increase in total estimated compression has to be met. Holmes has concluded that the calculated reduction of area is seriously in deficit of the amount required to explain mountain building. In reply, Jeffreys has sought to show that the folding seen in surface rocks is a different thing from the true shortening of the crust, being in part a secondary effect of the piling together of great thicknesses of sedimentary rocks. It is, however, true to say that the adequacy of thermal contraction as the main cause of mountain building is at least questioned.

With regard to the well-marked periodicity of mountain

building the thermal contraction theory supplies a partial explanation. It is conceived that the stresses gather continuously in the crust until the "strength" of the rocks is passed, when earth-movement begins. It continues until the stresses are relieved and then follows a period of quiescence during which the stresses again accumulate. Taking the rigidity of granite as fairly representative of that of the rocks of the outer crust, Jeffreys calculates that the compression at any place has had time to reach breaking point and to achieve relief about five times during the earth's past history. This figure is in rough agreement with the number of major mountain-building episodes. On the other hand, it has been contended that on the thermal contraction theory the interval between successive mountain makings should have increased as cooling progressed, whereas in fact, judged on other evidence, the interval seems to have remained about the same.

Other objections of very varying weight have been made to the thermal contraction hypothesis, and various replies have been made to them. The present position, however, is such as to justify us in reviewing some of the other forces which have been claimed as effective in mountain building.

Other theories of mountain formation.—It has been pointed out that the slowing down of the earth's rotation by the frictional drag of the ocean tides on shallow sea-bottoms, involves a small bodily contraction of the earth and a tendency to approach more nearly the true spherical form. It has been convincingly demonstrated that the contraction thus caused must have been small in total amount and must have taken place early in the history of the earth. The later phases of mountain building certainly cannot be ascribed to it. The claims made for several other real, though small, forces of the same general order of magnitude may be similarly dismissed on grounds of quantitative inadequacy. Such forces can, at best, be no more than minute supplements of the main force involved, whose magnitude is sufficiently attested by the results it produces.

Certain American geodesists have urged that isostatic adjustment, following the loading and unloading of "columns" (p. 28), gives rise to large vertical movements which are regarded as the essential element in mountain building. This view has been widely adjudged a complete

misreading of the mountain problem and it implies a failure to realize the enormous extent of horizontal movements visible in such regions as the Alps. Isostatic forces come into play during and after the tectonic disturbances caused by other forces ; they modify, but do not originate, mountains.

The theory of thermal cycles put forward by Joly (p, 52) carries with it a corollary in regard to mountain building. He points out that during a period of sub-crustal fusion, as conceived by him, the crust will be in a state of tension, but with the setting in of the phase of solidification in the molten under-region shrinkage would ensue. During this phase he represents the sea-floor as bearing against the continental margins, leading to crushing inwards and mountain building, while the sea-floor itself is thrown into long gentle undulations. Though the general theory of continental submergence put forward by Joly would seem to contain an essential element of truth, which holds out hope of a correction and elaboration of the hypothesis, the details have been too severely criticized to render his explanation of mountain building acceptable in this simple form. It has a certain plausibility as applied to the circum-Pacific chains, but it fails to account for the absence of mountain-folds parallel with the Atlantic coast, nor does it accord to the mid-continental Old World ranges any clear or convincing place in the general tectonic picture. It may be noted, however, that Joly's account emphasizes very strongly the essential distinction which must be drawn between the horizontal compression leading to folding and the entirely separate element of vertical uplift, two distinct processes, both of which are necessary in the formation of a mountain range.

During the last decade attention has tended to concentrate upon the plain indications of a definite relation between mountain building and continental drift. Wegener regarded the frontal edge of the drifting continents as being naturally crumpled against the resisting sea-floor. Argand and Staub have treated the spectacular crumpling of the contents of the Alpine geosyncline as due to the northward movement of the African block relative to the main European land-mass; while in his remarkable synthesis of the tectonics of Asia Argand has invoked a similar " jam," during a common southward movement, between the older masses of Siberia and

Peninsular India, as the cause of the younger mountain folds of Central Asia. We have seen, too (p. 81), that the much less ambitious conclusions of Lake in regard to the Asiatic mountain and island arcs, point to an outward creep of the edge of the Asiatic Continent.

In discussion of these related, though discrepant, hypotheses there is some danger of begging the question. In a search for forces that are quantitatively adequate it is plainly no use to represent continental drift as the cause of mountain making unless forces adequate to produce continental drift are in view. In particular, Wegener's presentation of the case has suffered a severe handling on the ground of the almost ridiculous insufficiency of the forces invoked. Moreover, it has quite fairly been

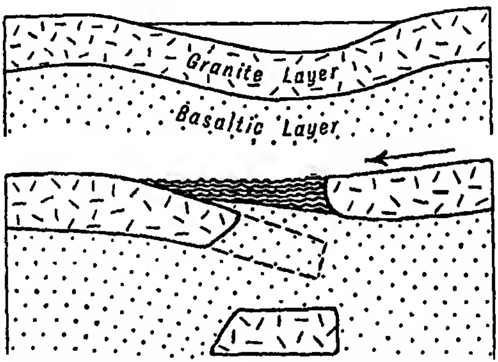
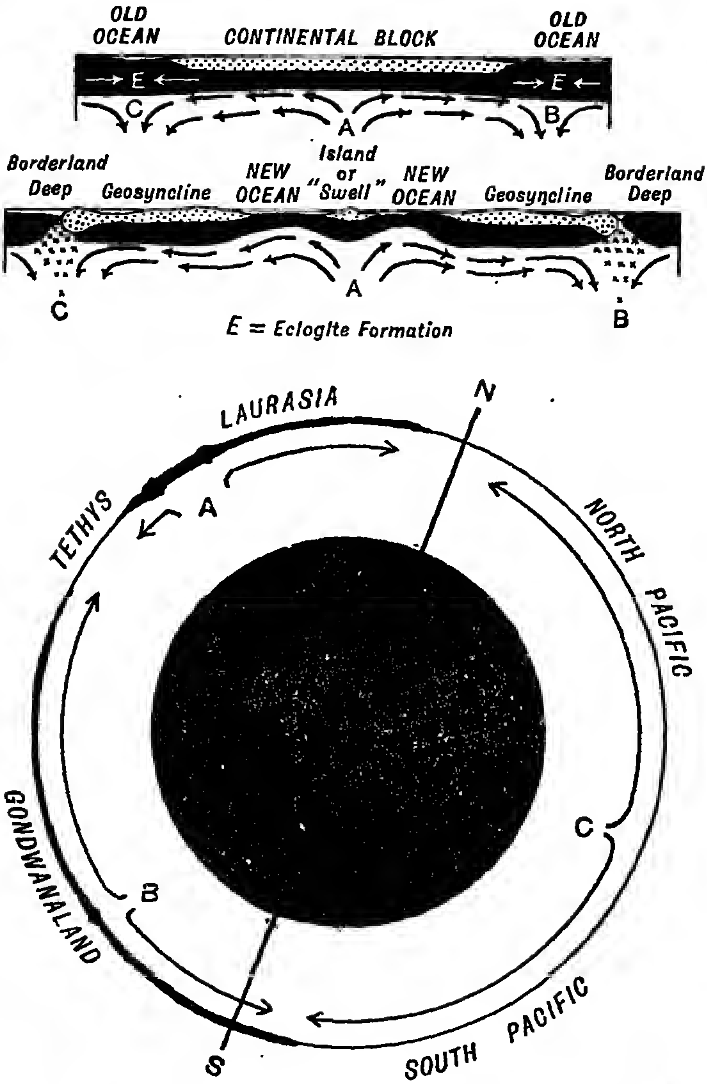


Fig. 71.—Daly's Theory of Mountain-building.
Crumpling of contents of geosyncline by downward sliding of the crust.

pointed out that totally different kinds and directions of continental drift figure amongst current hypotheses.

Daly has sought to retain the conception of frontal crumpling of continental masses, and at the same time to remove the reproach of an inadequate activating force, by imagining major bulges and hollows in the surface of the earth-ball, such that the continents may literally slide downhill over a glassy substratum (Fig. 71). Complete rejection of the idea may be premature; but it is fair comment to say that the cause of the primary "bulges" which start the slipping has in no sense been satisfactorily indicated.

The only unifying theory which shows hopeful signs of reconciling certain of the divergent hypotheses of mountain



[*After Holmes*.

FIG. 72.—SUB-CRUSTAL CONVECTION.

The sections above show fission of a continental block under the influence of outward-moving sub-crustal currents. Below, possible general scheme of planetary currents modified by action of continents. The name "Laurasia" refers to the great northern land-mass of former times comprising parts of North America (Laurentia), Europe and Asia. Holmes believes that rocks of high density similar to the type called eclogite form near the front of the drifting masses and sink (points B and C).

building and continental drift is that due to Holmes. It is based, fundamentally, upon his view that excess of radio-active heat in the substratum must maintain a condition of fluidity or mechanical weakness permitting existence of convection currents. Fluctuations in the state of the earth's magnetic field have independently suggested the existence of such currents. Reasons are adduced for supposing that there must be a veritable planetary circulation of currents in the substratum, somewhat analogous to the wind systems of the atmosphere. This very attractive analogy must do much to commend the theory to the interest of the geographical student, though, indeed, the theory rests on much stronger grounds than such mere analogy. Holmes suggests that there is a rising current beneath the equator, and a drift thence polewards in the upper portions of the substratum, with descending currents in the vicinity of the poles. Superimposed on this planetary circulation, he conceives another, caused by the blanketing effect of the continental masses, which hinder the escape of heat from the substratum and give rise to an ascending current beneath them. This is represented as feeding currents which flow out radially beneath the continents and which are therefore analogous to monsoon winds (Fig. 72).

CHAPTER X

THE ORIGIN AND CHARACTERISTICS OF ROCKS

The geological cycle.—The geological processes concerned in building and moulding the external parts of the earth are cyclical in their relations. The atmospheric destruction of the first land-surfaces provided the raw material for the first sedimentary rocks. These materials accumulated originally as unconsolidated sediment. Compacted by the weight of succeeding layers and hardened by natural rock-cements deposited from water, they were upheaved in due course to form new land areas, destined to similar atmospheric destruction. The first sedimentary rocks must have been derived from the outer crystalline shell of the planet, but thereafter each successive generation of sediments has received a quota, perhaps a predominant quota, of material from the break-up of older sediments. The great periods of uplift, however, have invariably been accompanied by the rise of molten rock into the sedimentary crust. Opinion is divided as to whether this molten material emanates entirely from the primary magmatic sources below the sedimentary cover, or whether it may not derive in part from fusion of deep-buried sediments. The point is immaterial for our present purpose. From whatever source they have come, igneous rocks have formed part of the land-surfaces at all stages of geological history.

In these broad terms we may envisage the geological cycle, which has run its course many times during the period of decipherable geological history. The great Scottish geological pioneer Hutton, who first clearly perceived the cyclical nature of earth history, could perceive " no trace of a beginning, no prospect of an end." The beginnings of the process are, indeed, inevitably lost in obscurity, but we can deduce the characteristics of the early cycles from the plainly written record of their successors.

The geological cycle must be viewed as a whole if its several parts are to be fully understood. Nevertheless, the growth and elaboration of geological science make it legitimate and, indeed, necessary to recognize some

differentiation of interest, or at least of emphasis, as between geologists and geographers. The processes of erosion are engaged in producing simultaneously land-forms and sedimentary deposits. Rocks, whether igneous or sedimentary, constitute on the one hand the manuscripts of past earth history, on the other the basis of contemporary scenery. Thus the study of sedimentation, and of the original environment in which rocks formed, is a major preoccupation of the geologist. His aim is the ranging of the rocks in age-order, the determination of their organic contents, and the reconstruction of past geographies. For the geographer of broad outlook these aspects have considerable interest, more particularly as showing that the distributions studied by him are simply the last term of a long line of past distributions, significantly related to the present. They are not, however, his main concern. Erosional processes concern him chiefly in their role as the shapers of landscape, while rock-masses enter his sphere of study chiefly as the constituents of landscape, or the material basis of regions. The study of these matters, however, involves some knowledge of the origin and of the physical and chemical characteristics of rocks. The purpose of this chapter is to treat briefly of these topics, as a preliminary to the study of erosion and landscape.

The classification of rocks.—The most fundamental distinction among the rocks of the earth's crust is that between the crystalline (igneous and metamorphic) rocks and the clastic or sedimentary rocks. The former have consolidated from a state of fusion, or assumed the crystalline state under the influence of great heat and pressure. The latter represent deposits, accumulated in water, or on the land-surface. The distinction is, indeed, evident enough if we compare a coarse-grained crystalline rock with a sand or mud rock only slightly consolidated. It is less evident on comparing a fine-grained crystalline rock with a hardened and compacted sediment which perhaps has suffered "cementation" by chemical substances derived from solution in water. In the early days of geological science the distinction was not, in fact, appreciated in such cases, and only by means of microscopic examination were the differences at length firmly established.

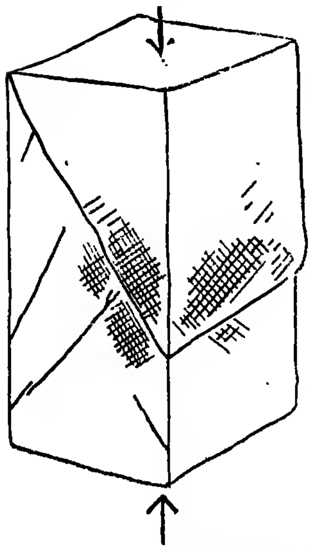
The crystalline rocks almost invariably form compact and resistant masses, but the sedimentary rocks vary

greatly in these regards, according to their state of "lithification." All transitions exist between incoherent sands, muds, etc., and compacted or lithified masses, which accord with the popular conception of "rocks." Lithification is the result of the physical and chemical processes incidental to burial under later sediments, and to earth-movements. Broadly speaking, therefore, the older sediments, bearing in their substance the stamp of long and complex histories, are "hard" or resistant, as compared with their younger analogues. It is essential to realize, however, that though this is a commonsense working rule, borne out fairly widely in practice, there are exceptions to it. For example, some of the earliest (Cambrian) sediments of West Russia have escaped lithification: they are clay and sand, comparable with the Tertiary sediments in Britain. On the other hand, the Cretaceous and Tertiary limestones of Southern Europe compare essentially in mass character with the older limestones of Palæozoic age.

The divisional planes of rocks.—All rocks which have achieved a certain minimum degree of coherence are traversed by divisional planes which impart directional properties to the mass. In the sedimentary rocks the primary divisional planes are the *bedding planes*. These mark changes in the character of the sediment or pauses in deposition. Certain igneous and metamorphic rocks also reveal original structures in the nature of streaking or banding. Such structures may consist essentially in the parallelism of constituent crystals. In other cases such parallel crystal orientation is combined with a separation into bands of contrasted mineral composition.

Of greater importance in the architecture of rock masses are the *joints*, developed in general after the consolidation of the rock. Joints are fractures in which little or no movement parallel to the walls of the fracture has taken place. In igneous rocks they may arise by contraction on cooling. In sedimentary rocks they are due in some cases to contraction in drying-out, or to widespread tension incidental to general uplift. Where rocks of either class have been involved in active earth-movement regular systems of joints have undoubtedly arisen through the operation of compression, tension, or torsion (bending), or through a combination of such forces. As a simple instance, we may note that tension joints tend to develop in the crest region of an anticline. Compressional and

torsional joints can be imitated experimentally. Thus, if a block of wax is subjected to compression upon two opposite faces, fractures, mutually perpendicular and inclined to the direction of compression at about 45° develop in the mass (Fig. 73). Similar intersecting fractures can be developed in a strip of glass by a bending or torsional movement. Joints may also be developed in exposed rock masses by the alternate expansion and contraction following diurnal changes of temperature (p. 147).



After Daubrée

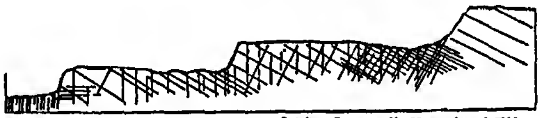
FIG. 73.—JOINTS DEVELOPED IN WAX PRISM UNDER COMPRESSION.

Examination of rocks in the field shows that jointing, while often complex in detail, shows considerable elements of orderly arrangement. Notable instances are afforded by certain of the basic igneous rocks, which develop amazingly regular polygonal columns bounded by intersecting joints roughly perpendicular to the cooling surfaces, *i.e.* the boundaries of the mass. In sedimentary rocks it is usual to find three sets of joints respectively parallel to the bedding, dip, and strike directions, and thus serving to divide the mass into cuboidal blocks. In some cases the bedding joints have developed along and emphasized the original bedding planes, but this is not necessarily the case. In large intrusive rock masses, a similar fairly regular cuboidal jointing is common. While regular joint systems are thus familiar and widespread, it is usual to find two or more of such systems independently developed at different times and intersecting one another at acute angles. This greatly complicates the jointing pattern. The *dominant* joints of a rock mass are sometimes called *master-joints*.

It is needless to enlarge upon the control exercised by jointing on the detail of scenery. Joints provide the natural avenues of attack for the weathering agents; and the long-period quarrying of natural denudation imitates in modulated fashion the harsher details of a man-made

quarry face. It is well to note, however, that the delicate etching of the land-surface by water, wind, and ice can reveal and react to slight differences in the strength of development and closeness of spacing of joints such as would defy investigation by eye or hammer. Weathering and erosion emphasize the jointing plan, bringing to light the places where it is weakly developed. Within an essentially homogeneous rock mass, variations in the intensity of jointing may impart large differences in mass resistance to weather and water (Fig. 74). We may legitimately suspect that the regular valley network of many regions depends in part upon the existence of master-joints, which are inconspicuous in artificial rock exposures.

Igneous rocks.—The igneous rocks have consolidated from a state of fusion. In the majority of cases they are composed wholly of mineral crystals lying in close contact, and separated by more or less rectilineal boundaries. In some, however, there is a residuum of mineral glass in



[*After Longwell, Knopf and Flint.*

FIG. 74.—CONTROL OF SURFACE DETAIL BY VARIATION IN THE INTENSITY OF THE JOINTING.

which isolated crystals are suspended. These rocks are, as a whole, relatively hard, and water penetrates only with difficulty along the inter-crystalline boundaries. Long exposure, however, can lead to deep rotting, and, exceptionally, the rocks may become so soft that they can be dug out with a spade. They disintegrate readily under the action of mechanical weathering (p. 146). As a class they are well jointed, the joints forming in many cases as a result of contraction on cooling. These joints are the only planes of weakness in the otherwise massive rocks, and well-developed joint systems may be rendered visible in the process of differential etching performed by erosion. They also facilitate the percolation of water through the mass and in virtue of their presence some igneous masses are water-bearing and oil-bearing.

As regards mode of occurrence, a distinction must be made between *lavas* (extrusive), poured out on the surface by local volcanic vents or welling up through fissures over wide areas, and *intrusions*, whose form and size are very various, and which represent molten rock forced

into the crust well below the surface and exposed only by subsequent denudation (p. 106).

The texture or coarseness of grain of the rocks bears an evident relationship to the mode of occurrence, since it depends on the rate of cooling and retention of the water and gases of the molten magma. The larger igneous intrusions, emplaced originally far below the surface, cooled slowly, and during crystallization retained in large measure the "fluxes" (water and gases) present in the original melt. These fluxes lower the crystallization temperature and hence extend the period of cooling. Such rocks are coarse grained. By contrast, lavas erupted at the surface or beneath the sea are rapidly chilled, and their crystallization is further hastened by rapid loss of fluxes. They are characteristically fine grained; indeed, some were chilled so rapidly as to consolidate in a glassy form, with a few crystals dispersed through the mass. Such glassy lavas have generally suffered slow crystallization or "devitrification" since consolidation, and hence they take on the character of very fine-grained crystalline rocks.

The range of composition of igneous rocks is very great, but for general purposes it is convenient to divide them simply into two main classes, styled acid and basic. The terms are rather misleading, referring simply to the silica percentage. Nevertheless these two main divisions, though linked by intermediate types, correspond to the two main zones of the earth's external region, referred to in an earlier section as the sial (acid) and the sima (basic). The acid rocks normally contain the mineral quartz, together with white or pink felspar; but with only small proportions of the darker coloured and heavier minerals, rich in iron and magnesium. They thus tend to be pale-coloured, and are generally hard and resistant to weathering. The basic rocks are heavier and darker coloured, containing high proportions of the so-called ferro-magnesian minerals together with felspar, which, however, differs in composition from the felspar of acid rocks. They are on the whole softer, and weather more easily.

Metamorphic rocks.—The metamorphic rocks are of very diverse origin, since they may be formed by the re-constitution of any igneous or sedimentary rock. They may arise through a simple operation of heat on the rocks round the periphery of an igneous intrusion, but the area covered by such rocks is generally too small to make them a geographically significant class. Much more

important are the great masses of metamorphic rock which have resulted from what is often called *regional metamorphism*, *i.e.* deep burial of rock masses, themselves originally igneous or sedimentary, under a sedimentary cover, and consequent subjection to high temperatures and a general shearing or flowing. due to earth-movement. Such rocks become wholly crystalline, or if the original rock mass was already crystalline there is a more or less complete re-crystallization of the minerals or the formation of new ones, and, in the result, the metamorphosed rocks imitate the coarser-grained igneous rocks in most of their characters, containing many of the same minerals and showing the same general massive characters. An almost universal feature is the presence of a streaking or parallel arrangement of their constituent crystals, which all lie with their longer axes pointing in the same direction. This structure is known as *foliation* and it may to some degree simulate the bedding of sedimentary rocks, imposing a directional feature upon outcrops and facilitating differential attack by weather. The coarser-grained metamorphic rocks, in which foliation is only imperfectly developed, are known as gneisses ; the finer-grained rocks, with more perfect parallel structures, are known as schists. In schistose rocks minerals of the mica group, which possess a natural platy habit, are frequently developed to a large extent. Fine-grained muddy rocks, subjected to regional metamorphism, become slates whose characteristic feature is the presence of numerous closely-spaced parallel planes of splitting or *cleavage*. Cleavage may be regarded as a special case of foliation, for it arises through the slewing round into parallelism of all platy and elongated minerals, some of which are probably produced in the metamorphic process itself. Slates, in fact, may be regarded as a special type of fine-grained schist. With increasing intensity of metamorphism they pass to phyllites or fine-grained mica-schists. Brief reference may also be made to the result of metamorphism acting upon a sand rock. The product is the extremely hard rock type known as quartzite, generally white in colour and consisting of quartz crystals in intimate contact. In addition to extreme hardness, quartzites possess the property of virtual chemical indestructibility. Since quartz is exceedingly stable in all save extreme conditions of weathering, massive quartzites are salient elements in landscape, often simulating the effects of igneous sills

and forming prominent ridges. The term quartzite is also extended to sandy rocks which have been subjected to cementation by silica deposited from solution. Such rocks are generally softer than the true metamorphic quartzites and often behave more like normal sandstones, breaking down into a sandy soil.

Sedimentary rocks.—The three major classes of sedimentary rocks—in broad terms the sandstones, the clays or shales, and the limestones, build by far the largest part of the present land-surfaces. Though all three types, and especially the sandstones, may accumulate in fresh water or on the land-surface, the sedimentary cover of the continents is essentially marine in origin, representing accumulation in shallow epicontinental seas which have extended across the continental surfaces during periods of "marine transgression." Before studying their features it will be well to glance at the general process of origin of these rocks.

At the present time the coarser varieties of sedimentary rocks, gravels, beach-deposits, pebble-banks, etc., are confined to the littoral or the proximity of the shore. Extensive deposits of sand and of silt mantle the continental shelf, which extends to varying distances from the shore. At a depth of about 100 fathoms the so-called "mud line" is generally encountered—a relatively narrow zone of transition between the sands and silts and the finer material worn from the lands which goes to form the typical "blue muds" of the ocean. Such deposits extend down the continental slope to an average depth of 1,000 fathoms, and constitute, by far, the most important of the true mud deposits accumulated in the sea. These blue muds are the modern representatives of the older clays and shales. It will, of course, be clear to the reader that the "mud line" is not literally fixed in position; locally it may approach the land, while, elsewhere, it recedes from it, where larger quantities of sandy detritus are discharged from the rivers. Moreover, muds rich in organic material are characteristic of the larger estuaries; they constitute a distinct class of deposit, closely associated with the sands of the shallow off-shore waters.

Limestones.—The formation of limestones requires no special conditions of depth, but reflects rather clear water conditions. Thus, while it is true that many limestones form far from land, out of reach of land-borne sediment, have often accumulated in shallow water near shore

when from any cause the supply of land-borne sediment was in deficit. For example, off the shores of a continent of low relief drained by sluggish rivers, or possessing a desert climate, it has been no uncommon thing for limestones to accumulate to within a short distance of the margins of the land. Such is believed to have been the case of the Chalk of North-west Europe, which formed off desert shores, and grades landward into a sandy zone of surprisingly small width.

Not only is it impossible to set any precise limits to the depths in which limestones can form,[1] but we also have to realize that the modes of formation are exceedingly diverse. The more extensive limestone formations owe their substance to the calcareous skeletons, complete or comminuted, of invertebrate organisms living in the sea. Most of the marine invertebrates build calcareous skeletons which range in size from the minute shells of foraminifera to the comparatively massive and complex structures built by cephalopods. Organisms with this lime-secreting habit may live in the surface waters, on the sea-bottom, or in intermediate depths, but in all cases where the water is sediment-free, their remains will tend to accumulate as the raw material of limestone beds. It is worth noting that both in modern coral reefs and in certain of the shallow-water limestones of the past, lime-secreting seaweeds (calcareous algæ) play a very important part in limestone-building. Similar, though less extensive, accumulations of calcareous skeletons may occur in fresh water, though the range of organic types which contribute to such deposits is much more restricted than in the sea.

There are at least two other important modes of limestone formation which may act concurrently with the accumulation of organic remains, or in special circumstances may operate alone. In the first place, calcium carbonate may be deposited directly from solution giving "chemical limestones" as distinct from "organic limestones." Since the solubility of calcium salts decreases with rise of temperature such deposition is especially liable to occur in warm shallow waters, where the calcareous content is high. It is under these circumstances that the well-known oölitic limestones are often formed, pellicles of limestone growing, layer by layer, round

[1] There is a superior limit of depth in the deeper parts of the ocean below which limestone cannot form and where it gives place to siliceous deposits. owing to their lesser degree of solubility.

sand grains, shell fragments or some such nuclei, and thus forming small spheroidal pellets which constitute a sort of calcareous sand. Calcium carbonate may also be deposited from fresh water, as in lakes, or from springs (calcareous tufa, calc-sinter, or travertine), but with few exceptions the masses of limestone thus formed are of inconsiderable bulk. A second supplementary method of limestone formation, again not due directly to organic agency, consists in the break-up and re-deposition in the form of ordinary sediment of limestones of earlier formation. While, in such a case, some of the material inevitably goes into solution, some of it may survive transit in solid form, either as a calcareous mud or as a mass of larger limestone fragments, ranging in size from sand grains to boulders. Thus, some of the limestones of the English Lias have been regarded as "detrital limestones" formed by the break up of such older masses as the Carboniferous Limestone. In the latter formation itself, certain layers (the so-called calcite mudstones) may have had a similar origin, while the famous Nagelfluh formation of the Northern Alps is a conglomerate made up of rounded fragments of older limestones.

It is an important characteristic of all limestone rocks that they are "self-cementing." Neither great age nor the pressure of overlying beds is necessary for their assumption of a hard, stony or "crystalline" condition. This arises from the solubility of their principal component in normal atmospheric or ground waters containing carbon dioxide in solution. The passage of such water through pore-spaces and divisional planes secures that a large part of the mass temporarily enters the state of solution and is re-deposited in a crystalline state. In this fashion many organic limestones such, for instance, as the Carboniferous Limestone, suffer an extensive obliteration of their original structures, the outlines of the original skeletal components being lost in the process. It should be noted, however, that the fine-grained impalpable "powder" (whether it be comminuted shell material or chemical precipitate), which fills the spaces between the larger shells or ossicles, suffers re-crystallization more readily than these larger masses. Clear traces of organic origin may thus survive re-crystallization in favourable cases.

The fact that many limestones are styled "crystalline" must not lead the student to confuse them with the crystalline igneous and metamorphic rocks. Though

entitled to rank as crystalline rocks in the narrow sense of the term, their geological origin and their geographical characters, particularly their comparative softness and solubility, place them in a wholly different category.

Magnesian limestones.—The only other class of calcareous rocks whose origin deserves brief mention is that which embraces the " magnesian limestones " and dolomites. In these rocks part of the calcium carbonate of the true limestones is replaced by magnesium carbonate. Salts of magnesium, which rank next to sodium chloride as important constituents of sea-water, provide a source of magnesium carbonate for the formation of such rocks, which accumulate only in marine or semi-marine environments. The process of dolomitization, in which the magnesian element is introduced into the rock, may take place during or just after the accumulation of the limestone ; in this way, large accumulations of original or contemporaneous dolomite may be formed. Favourable circumstances are often realized in the warm shallow waters of coral lagoons, or in partially enclosed seas subject to high evaporation, whereby the magnesium salts are concentrated. Dolomitization may also be " subsequent," taking place after the limestone has been consolidated and upraised. In such cases it commonly follows the passage of saline waters along joints in the mass, the dolomite appearing as patches or veins in the limestone. A dolomite is less soluble and more resistant to normal weathering than a limestone—a fact which warrants its separate recognition for geographical purposes, and also adds greatly to its value as a building stone. The constituent dolomite crystals which build the rock are much smaller than the corresponding calcite crystals of limestones—not more than one-eighth of an inch in diameter. This fact, together with its yellow or brown colour, gives the rock a superficial resemblance to a sandstone, with which it is often confused by careless observers.

Rocks of continental origin.—In the foregoing short survey of sedimentation under shallow marine conditions we have reviewed the more important environments in which sand rocks, clay rocks, and limestones arise. It remains to note that the first two classes have not unimportant representatives which have been formed on continental surfaces, often under arid conditions. Large masses of sandstone have accumulated in the past, both in deserts and on coastal fringes, under the influence of

the wind, and they yield evidence of such an origin in the high degree of rounding and polishing of their grains, in their characteristic "dune-bedding," and (if formed under arid conditions) in their red colour, which is due to a pellicle of red iron oxide round each sand grain. Finer-grained rocks, belonging to the argillaceous class, may also accumulate under the action of the wind, as in the case of the loess, disposed peripherally round the desert interior of Central Asia and formed also over a wider area during abnormal climatic conditions of recent Ice Ages. The red "marls," which are common in many continental formations, probably also represent wind-blown material, arrested by shallow bodies of standing water—temporary lakes or "playas," due to heavy seasonal rains.

It is particularly in the case of the coarser fragmental deposits—gravels, pebble-beds, conglomerates, and breccias—that a continental origin has often to be invoked. Though marine conglomerates, representing ancient beach deposits or pebble shoals, are common, their thickness and extent are generally small. Larger masses of such material are generally to be referred to the work of rivers spreading coarse flood detritus, in flat delta fans, over the surface of intermontane basins or coastal plains. Many well-known sand and pebble-bed formations, such as the Old and New Red Sandstones and the Siwalik formation of the Himalayan foothills, are of such an origin, and comparable conditions are realized in Turkestan, Persia, etc., to-day. In these same regions we may witness the growth of fans of scree composed of angular debris, which mantles the bases of steep rocky slopes and provides a working demonstration of the formation of some of the notable breccia formations of the past, such as the "brockrams" of the Eden Valley or the breccias of the Clent Hills. Still other ancient boulder-beds are referred with great certainty to the work of valley-glaciers and ice-sheets, being analogous to the glacial drifts of more recent times. Some are consolidated sand, gravel, or boulder deposits, comparable with the morainic and outwash accumulations of existing glaciated plains, while others, the "fossil boulder clays," or *tillites*, show scattered angular boulders in a fine-grained argillaceous base.

The geographical characters of sedimentary rocks.—In dealing with the more important geographical characters of the chief sedimentary rock groups we are confronted with the difficulty that, in detail, their lithology is

infinitely variable, and that the main types constantly pass into one another by insensible gradations. Thus, we may pass from pure sandstones through calcareous sandstones to sandy limestones, or from pure limestones through marls to calcareous clays. In detailed geographical study it is essential to obtain full lithological information, for variations such as are noted above may import radical and significant modifications into land-forms. In some cases, indeed, lithological minutiæ may be more significant to the geographer than the geologist though, in general, the interests of both are served by careful and detailed lithological descriptions. In spite of these facts there is, undoubtedly, a tendency in sedimentation processes to the evolution of fairly well individualized types in respect of grading (grain-size) and composition, so that it remains possible to attempt some generalizations as to geographical character.

In the case of coarse fragmental rocks in a consolidated condition it may be said that they are commonly massive, showing few signs of bedding and but ill-developed jointing. Their resistance to weathering processes often depends more upon the hardness and solubility of the finer material occupying the interspaces than on the characters of the larger fragments. If the former is of low resistant power the rock readily falls to pieces, thus reverting somewhat closely to the conditions under which it was formed. All sign of coherence in the rock may thus be lost in the surface outcrops.

Sandstones, like their coarser analogues, show a tendency to a massive character. It is evident that the slight pauses in deposition, which give rise to bedding planes, will tend to produce less effect in a granular rock and, accordingly, well-bedded sandstones are comparatively rare. Where bedding is developed and the mass breaks up into slabs, the rock is often called a *flag* or a *flagstone*, though the same term is also used for argillaceous rocks. The softer sandstones are, as a rule, poorly jointed.

Grain-size can vary within wide limits. Coarse-grained sandstones with angular particles are frequently termed "grits" (cf. the Millstone Grit, the Harlech Grits), though unfortunately the same term, in English usage, is applied also to certain rough limestones made up of shell fragments. The finer-grained sandstones are technically "siltstones," their quartz particles ranging from 0·01 to 0·1 of an inch in diameter, and such a designation might fitly be applied

to many of the older sandstones in Britain, including those which contain a certain admixture of clay and which figure in older literature as "greywackes."

The outstanding characteristic of typical sandstones is their high porosity, the pore-space frequently rising to 30 per cent. of their total volume. It is evident that the pore-space depends on the shape of the grains, being greater with rounded grains than with angular grains which "pack" more effectively. This property renders sandstones, as a class, important water-bearing strata. The New Red Sandstones of the English Midlands take rank after the Chalk as the most important water-bearing horizon in Britain, a distinction which they owe, in large part, to the high sphericity of their desert-rounded grains. The porosity of sandstones has another important consequence in that, during formation and during and after uplift, they are subject to cementation by the deposition of various binding media in their pore spaces. The common cements are calcareous, ferruginous, and siliceous, though other substances figure locally. A siliceous cement imparts to the rock a high degree of durability and may lead to its simulating the characters of a true metamorphic quartzite; in particular, such a rock is frequently better jointed.

The argillaceous rocks are characterized by their general softness. Some exception to this statement must be made in the case of slates, though these, as we have seen, are really metamorphic rocks. Correlated with the general softness there is an absence of clearly cut divisional planes, such as may exercise structural control. The rocks are resistant to chemical weathering and erosion save under the extreme conditions of tropical climates, but they yield readily to mechanical agents, their outcrops being rapidly reduced to a state of low relief by normal erosion. They are essentially impervious to water, the available pore-space between the clay-particles being occupied by water films, which bind the mass together and contribute to its plasticity. This water will not run out of the mass, but is firmly held by the rock, forming, as it were, one of its essential constituents. As a result of this character the texture of the drainage on clay lands is fine and, through absence of structural control, it generally has a dendritic character (p. 189). Shales and clays act as the chief agents in arresting the downward progress of ground water; and, as such, they frequently are the active cause of land-slips, as may be seen in many coastline sections, and

also inland, as where the Upper Greensand of the Weald rests on the Gault Clay; in such cases the clay acts as a lubricant at the base of the sliding mass.

In Britain the chief true clay lands are situated upon the outcrops of the Carboniferous shales, the Keuper Marls (New Red Sandstone), the three great clay formations of the Jurassic rocks (the Lias, the Oxford Clay and the Kimmeridge Clay), the Weald Clay and the Gault of the Cretaceous system, the London and Barton Clays of the Tertiary beds. All these clay formations are closely similar in their main features, the approximation to type being greater than in the case of the sandy and calcareous rocks. The clay formations in the older rocks, originally accumulated under similar conditions, have generally suffered such changes through hardening and cleavage that their topographic expression is entirely different. Even in these rocks, however, the general uniformity of lithology and absence of structural controls is clearly seen in the subdued character of the resulting hills. Much of the slate country of Wales and the Southern Uplands of Scotland, the Ardennes, and of the slaty massifs bordering the middle Rhine valley is as featureless as Chalk downland.

The calcareous rocks, when they have suffered self-cementation, are in the broad sense hard, though their chief constituent mineral, calcite, is distinctly soft and is easily abraded by water-borne debris. Their hardness, on closer inspection, proves to be rather a resistance to denudation resulting from their other salient qualities. Limestones are *par excellence* well jointed and pervious to water. Even in chalk, a relatively soft and porous limestone, the chief water passages are the joints and fissures which traverse it. This well-jointed character frequently leads to the passage of ore-depositing solutions through the mass and the accumulation of small quantities of metallic ores in the form of "gash veins." It also secures for limestones a high place amongst water-bearing strata. The other outstanding character in these rocks is their high degree of solubility by water containing carbon dioxide in solution. Coupled with the jointing factor this renders the hydrology and topography of limestone areas highly distinctive and peculiar. The removal of the rock from the general surface takes place largely through solution, joints are widened into gaping fissures or clefts, while cylindrical "pipes," swallets or swallow-holes may

also be dissolved out by percolating water above the level of saturation. The drainage of a limestone district may be carried out largely by underground streams, leaving the surface valleys dry. Extensive underground caves may thus be formed, and surface subsidences not unfrequently result. We cannot here undertake a full description of limestone topography, for the subject is sufficiently important to demand separate treatment (see pp. 276–294).

Before leaving the subject of the geographical characters of rocks it will be well to give some attention to the natural associations or groupings of the sedimentary rock-types. Here again no rigid generalizations are possible, but certain undoubted tendencies exist which greatly facilitate geographical interpretation.

It is unusual to find sandstones and limestones recurring in an alternating series, but sandstones and shales and limestones and shales often show this relation. As an instance of the former we may cite the Coal Measures in Britain, and indeed in most other localities, and the Lower Cretaceous rocks of the Wealden area. The latter association is well illustrated by the Lower Carboniferous rocks of the North of England and the South of Scotland and by the Jurassic rocks of England, although in both cases sandy rocks enter as a minor constituent of the series. Further instances are afforded by the Silurian rocks of the Welsh border and of Eastern North America. In both associations we are witnessing the results of a migration in time of what the geologist terms a "facies boundary"—in the one case the normal "mud-line," in the other of a time-marking division between clear and muddy water (Fig. 75).

Both sandstones and limestones show some tendency to occur in thick individual masses or formations, the former often in association with coarse fragmental deposits of continental origin. The tendency is not shown to the same degree by the argillaceous rocks, though it would not be difficult to cite cases which constitute an exception to this generalization. It is worth while to reflect on the fact that all three classes of sediment are derived ultimately from the destruction of primary igneous rocks, of which granite may be taken as the typical and predominant member. Their total relative world-proportions are thereby fixed. The actual proportions deduced from the average composition of the igneous rocks work out as

follows : One part of limestone, two parts of sandstone, twelve parts of shale.[1]

The geographical limitations of geological maps.—In connection with the groupings of sedimentary rocks it will

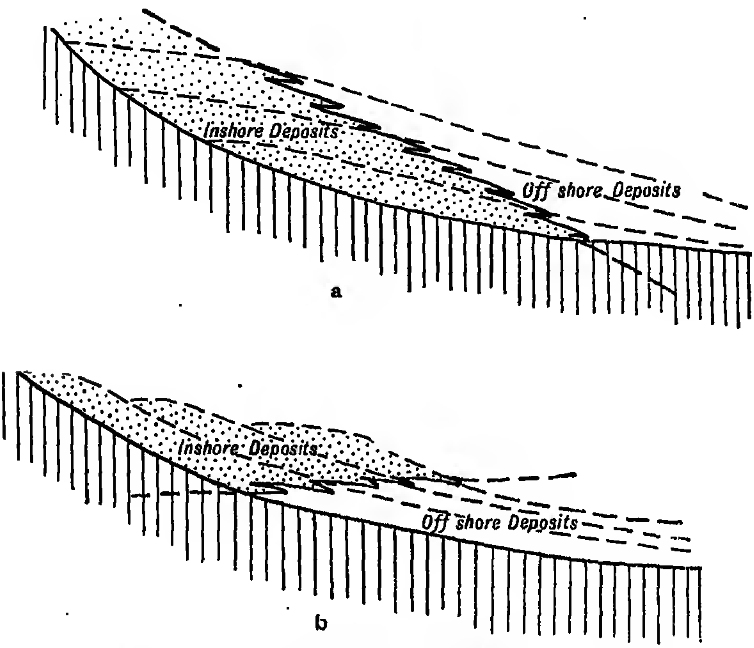


FIG. 75.—NON-COINCIDENCE OF TIME-PLANES AND LITHOLOGICAL PLANES.

The deposits of (*a*) advancing and (*b*) retreating sea. Dotted lines mark time-planes. In (*a*) the off-shore deposits encroach landward as the sea advances. Thus the deposits of any given time-stage are partly of in-shore and partly of off-shore characters and the boundary between the in-shore and off-shore sediments does not coincide with the time-divisions. In (*b*) the converse relation holds with similar results.

be well to point out some of the necessary limitations of geological maps, from the point of view of the geographer. The colouring on these maps primarily represents age, rather than lithology, and this may be most misleading,

[1] Working from a computed average composition of the igneous rocks it has been calculated that 100 grms. of igneous rock, together with the constituents added during atmospheric weathering, would yield 88 grms. shale, 13 grms. sandstone, 7 grms. limestone, and 6·5 grms. ocean salts (see p. 148). These proportions agree only very roughly with those deduced from actual measurements of the stratified rocks, which indicate a much higher proportion of limestone. Such measurements, however, are difficult to make accurate and representative.

if imperfectly understood. An excellent example is afforded by the group of beds known as the Coal Measures. Though these are now sub-divided to some extent, they generally appear on maps in one colour or in variants of one colour, the only individual beds of the series separately shown being the coal seams themselves. These are thin layers making quite an inconsiderable part of the series, *e.g.* in a generalized vertical section through, say, 2,000-odd feet of measures in some of our coalfields the workable coal seams are little more than 30 feet in total thickness. As a whole, the Coal Measures are, essentially, an alternation of shales with massive sandstones. The outcrops of some of the sandstones may indeed be indicated on the map, should they be readily traceable and, more particularly, if they can serve as a datum of reference for one or more valuable coal seams occurring near-by in the series. It must, however, be clearly recognized that any sandstone band so mapped is generally only one of many. The coal seams are, of course, important geographical facts, yet if the map were being made for purely geographical purposes, somewhat different aims would be pursued in the mapping. Similar difficulties arise in the case of other formations. The Weald Clay of South-eastern England, considered in the mass, does not belie its name; but it contains local developments of shelly limestone ("Sussex Marble"), and considerable and persistent sandstone bands. These are not shown on the map; but they are of great geographical interest, for the limestones form distinct escarpments which diversify the clay lowland, and the sandstones are sources of water-supply. Again, the characteristic earthy limestones in the lower part of the Lias are distinguished by no special colour on the geological map, but are included with the mass of shales and clays of which they form part; yet their influence on surface utilization and topographic form is quite evident. Consequently, the map must necessarily fail to serve all purposes equally well.

The geographer should constantly bear these facts in mind and realize the necessity of modifying and adding to the geological map for his own special purposes, or at least, of using it with discretion. It is, of course, fortunately true that most of the boundaries shown on the map are lithological boundaries; on the older maps they were almost wholly so. But a modern geological map is an admitted compromise between the "age method" and the "lithological method" of grouping rocks, and in its

production the art of judicious selection of the features to be shown needs constantly to be applied. The increasing perfection of geological cartography does, indeed, result in an increasingly careful sub-division of the beds. In some cases this process may exceed geographical needs, where large numbers of different colours are used for formations, which, while distinct, do not differ sufficiently among themselves to render each geographically significant. In such cases, as for example with certain of the newer maps of Wales, it may be an advantage to revert to older, simpler groupings of the rocks.

A word may also be said with regard to the treatment of " drift " deposits on maps. The distinction between " drift " and " solid " deposits on British maps is quite arbitrary, having no necessary relation to thickness or state of consolidation. It consists simply in separating the deposits of the most recent or Pleistocene period from those of all older dates. While this course is entirely defensible from some practical standpoints, it must be borne in mind that many older accumulations imitate the drift deposits in their inconsiderable thickness and general lack of coherence. The most logical and practical treatment of drift deposits is based upon their relation to the topography. If they have come into place after the landscape has taken on some close semblance of its present form their extent and mode of origin are generally obvious ; such is the case, for instance, with river and marine alluvia, rain-wash on slopes, etc. If, however, they form part of the general rock-mass out of which the landscape has been carved, all their relations are obviously different, and even though they may be, technically, " drifts," they differ in no important respect from many " solid " formations. For instance, the great sheet of glacial drift which mantles East Anglia is so thick that, were it removed, large parts of the area would be submerged. The valleys are cut through this sheet of deposits and often fail to reach its base. Thus, the " drift " is geographically analogous to the adjacent masses of sand and clay, which, however, simply because they are pre-Pleistocene, rank as " solid " deposits. This point is emphasized in view of a tendency, not yet dead, to regard the " drifts," as the older geologists regarded them, as mere " extraneous rubbish " of little importance. As is now well realized, these deposits often take front rank as geographical factors and may locally dominate all others in importance.

CHAPTER XI

SUB-AERIAL DENUDATION

THE complex process of rock-wastage or denudation which goes on continually over the surface of the continents comprises three distinct phases: (1) weathering, (2) transport, (3) erosion.

Weathering implies the breaking up or decomposition of exposed rock masses, thus rendering them fit for transport by moving water, ice or wind. The first two of these agents act under the control of gravity and are concerned in a general "downhill" transport of the products of weathering, whose ultimate home is the sea. Wind is subject to no such control, and under its influence great masses of rock material may accumulate, temporarily at least, on the surface of the continents. In all cases the moving grains of rock-debris are capable of performing erosion, producing a differential etching of the land surface, bringing into being various relief features or land forms.

Geomorphology shares with physical geology the detailed study of the processes of weathering, transport, and erosion. For our present purpose a summary of their action will suffice.

Weathering.—Weathering may be regarded as of two distinct kinds, according as the rock is disintegrated without chemical alteration (mechanical weathering) or rotted and decomposed (chemical weathering). Though both types of action commonly co-operate in producing the mantle of rock-waste, each has its regions of optimum development, in which it may be studied in relatively simple circumstances.

Mechanical Weathering

Disintegration is characteristic of the desert areas of the globe, where the clear dry air ensures a large diurnal range of temperature. Here the bare rock surfaces are highly heated during the day and the outer layers expand considerably, but during the night the temperature often falls close to freezing-point, with resulting contraction. This alternate expansion and contraction develop

a series of joints both parallel and perpendicular to the exposed surface and the rock tends to break into blocks, which cumber the base of the crags and spread in fans over the surrounding flat surfaces. This process may be appropriately termed "block disintegration." The peeling or "exfoliation" of certain rocks, which split into concentric shells, is a special case of the same process. In the case of most rocks, however, and of coarsely grained rocks in particular, the shattering proceeds farther, breaking the rock up into smaller pieces. Where the constituents of the rock are of different colours they absorb heat to differing extents, and possess different coefficients of expansion, so that complex internal strains are set up, which cause the rock to fall apart into its constituent mineral grains. This may be termed "granular disintegration."

A kindred shattering action takes place in cold climates. Rocks may become soaked with water during the day, owing to the melting of snow or ice; while during the night this interstitial water freezes, exerting an enormous expansive force. Here, again, block disintegration results, with further comminution of the blocks as the process continues.

In both desert and polar regimes disintegration is unaccompanied by any appreciable chemical change.[1] In both types of region, accumulations of scree or talus are found round the bases of steep slopes, and these may develop into great fans which spread steadily outwards.

Scree formation through frost action is particularly conspicuous amongst the higher mountain peaks, even in temperate climates. The surface of a scree tends to an angle of rest or stability which depends upon the coarseness of the constituent blocks, but the equilibrium is constantly disturbed by fresh falls and the whole mass moves gradually downward, thereby burying large areas.

Chemical Weathering

The chemical decomposition of rocks comprises several processes which are usually concurrent, though one or other may be dominant locally. Simple solution plays its part, and where masses of rock-salt, gypsum, etc., are

[1] In desert climates, waters with mineral matters in solution may rise to the surface by capillarity. There they become concentrated by evaporation and may give rise to chemical corrosion. Further, the crystallization of such solutions, involving expansion, leads to mechanical disintegration.

exposed to its action the results may be notable. Hydration also is a widespread phenomenon. Many of the rock-forming minerals are able to take up additional water, and the hydrated alteration products commonly occupy a larger volume, and are softer, than the original minerals. The fact that rain water and surface water generally, as well as ground water, all contain dissolved atmospheric oxygen, renders oxidation a universal feature in weathering. This is particularly noticeable in its effect upon iron compounds. In surface rocks these compounds generally show the red, yellow or brown tints indicative of a high state of oxidation; iron-oxides (generally hydrated) are, in fact, among the commonest pigments in exposed rock masses, while, at greater depths, the grey or blue colours characteristic of iron compounds poorer in oxygen predominate.

Of much greater general importance is the process of carbonation (carbonate-formation), which may be regarded as the dominant weathering process of the humid temperate regions. Rain water dissolves an appreciable quantity of carbon dioxide from the atmosphere and thus becomes, in effect, a dilute solution of carbonic acid (H_2CO_3). The rivers of temperate regions contain large quantities of carbonates, which have been produced by the action of surface waters containing carbon dioxide upon the bases in the rock. In the case of simple felspar, one of the most important constituents of the crystalline rocks, the reaction may be written thus:

$$\underset{\text{(orthoclase felspar)}}{K_2O\ Al_2O_3\ 6SiO_2} + 2H_2O + CO_2 \rightarrow Al_2O_3\ 2SiO_2\ 2H_2O + 4SiO_2 + K_2CO_3$$

It is perhaps more instructive to write the equation in a more general form to bring out its geological significance thus:

Crystalline felspathic rocks + rainwater → clay + sand + carbonates in solution

It is important that this equation should not be interpreted in too literal a spirit, but properly understood it gives the clue to the weathering of temperate regions, and to much else in physical geology. In a granite area, for example, we may think of the carbonates being dissolved out in this way, leaving a potential residuum of mixed sand and clay. In general the residuum does not, of course, accumulate, but is carried away by running water

and sorted in the process into its two constituent parts, which are deposited in due course in a relatively pure form. It should be remembered that the reaction is not applicable only to potash, *i.e.* orthoclase, felspar, but to felspars with other bases, *e.g.* soda and lime, as well as to all the other aluminous silicates, such as the micas, augite, hornblende, etc. Hence in essence all crystalline rocks—as well as those sediments containing some unaltered silicates—are liable to this type of decomposition. The only addition which we need make to the statement concerns the disposal of iron compounds which are generally present in the original rock. In such a case, hydrated iron oxide (limonite) will accumulate with the sand and the clay, colouring them some shade of brown, and possibly acting as a cement.

The process of carbonation can obviously have no effect upon pure sand or clay rocks exposed to weathering, since these are themselves end-products in the process and not susceptible of further change. Limestones, however,

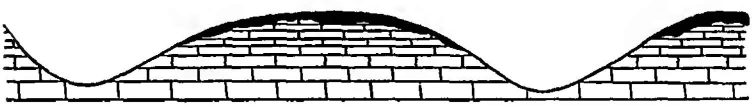


Fig. 76.—Residual Clay-with-Flints capping Chalk Ridges.

afford a rather special case, in which carbonation assumes a dominant rôle. Calcium carbonate (the material of limestones) is only slightly soluble in pure water, but is readily dissolved by a dilute solution of carbonic acid, such as is represented by rain water. Hence we find that solution has powerfully affected certain limestone areas, such as the Chalk tracts of Britain or France. On flat plateau surfaces the Chalk has for long periods been undergoing continual dissolution, while the insoluble residue of clay and flints has accumulated as an irregular mantle, sometimes to a thickness of many feet (Fig. 76). This is the origin of the "clay-with-flints" of the English Chalk country (Fr. *argile à silex*). In the limestone tracts of Southern Europe a similar accumulation, the "*terra rossa*" (red earth), is widely developed, though under somewhat different climatic conditions. These are examples of "residual deposits" left in the process of weathering.

Though the effects of chemical weathering are plainly

traceable throughout the regions of humid temperate climates, it is in the equatorial regions of great heat and moisture that they reach their maximum. The prevalent high temperatures greatly stimulate the solvent and chemical action of the surface waters. Rotting, even of hard crystalline rocks, may extend some hundreds of feet below the surface. In these regions the common end-product of weathering is the material known as laterite. Laterite is a red-brown, clay-like substance which derives its name from the fact that when freshly cut it will harden on exposure to a brick-like consistency (Lat. *later-*, a brick). It proves on analysis to consist essentially of hydrated aluminium oxides (such as bauxite $Al_2O_3,2H_2O$) mixed with the oxides of iron and manganese which give it its colour. It results from the decomposition of widely dissimilar rocks, including basalt, granite, gneiss, slate, and sandstone, and it covers extensive areas in the tropics. While its origin has given rise to considerable controversy, all are agreed that it is essentially a residual deposit, though locally reconstructed at low levels by running water. If we compare clay, as a typical weathering product of temperate regions, with laterite, the chief chemical difference is the absence of silica in the latter. Although the exact mode of removal is still in some doubt, the leaching out of silica is a salient feature of tropical weathering, as is made manifest by the analysis of tropical river-waters, which are much richer in silica than their temperate analogues. In temperate regions the silica of weathered rocks is largely (though not entirely) immune from solution and it accumulates, or is re-deposited, as sand, or it remains partly in chemical combination, as in clay. In the tropics silica of the last category is very largely extracted in solution. The residual deposits are thus chiefly oxide mixtures, such as laterite.

In viewing the nature of weathering as a whole it is well to bear in mind that although its several aspects may conveniently be treated separately, they must normally be regarded as overlapping. The several processes co-operate and supplement each other to a large extent, especially in temperate regions. In particular, mechanical comminution is often a powerful aid, if not an essential preliminary, to chemical attack. The end of weathering is the production of a mantle of broken rock fragments, large or small, such as covers the greater part of the land

areas. This mantle is subject to continual movement by means of slipping and "hill-wash." Wherever it exists it represents a local balance of accumulation over removal by transporting agents. Its superficial portions, modified by contact with the atmosphere and with plant and animal life, form the soil, which, however, has its own complex problems, physical, chemical, and biological.

It will be noted that the progress of weathering does not depend upon the hardness of the rock, but upon such factors as chemical resistance and the degree to which it is traversed by divisional planes. It is well, therefore, not to speak of "hard" and "soft" rocks without careful consideration. Actual hardness—*i.e.* resistance to abrasion—is a factor in landscape where active erosion is concerned, but the relative protuberance of rock masses must often be ascribed to varying resistance to weathering.

Erosion.—The chief agents of sub-aerial erosion are water, wind, and ice. Of these water is the most important, since water erosion must be regarded as the normal means of land sculpture over the greater part of the land surfaces of the globe. Even where arid conditions are well-established and the work of wind is paramount, the action of water makes itself strongly felt after the fall of sporadic convectional rains. Elsewhere, arid conditions may supervene merely as a temporary climatic phase, and thus modify, but not obliterate, the characteristic effects of water sculpture. Similarly, glacial conditions may prevail temporarily in a region normally subject to water erosion, but the results of the work of water, accompanying or alternating with the glacial phases, are clearly legible in the land-forms.

The major land-forms of the earth's surface derive some features of their form and distribution from the direct effects of tectonic movements, but even these larger features are substantially modified by the persistent attack of the agents of weathering and erosion. The minor relief features of the landscape are, in normal circumstances, entirely due to differential erosion, the valleys being forms of excavation and the hills merely residual masses. This view of relief features was not widely accepted until well on in the nineteenth century. Lyell in 1838 still represented the valleys of the Weald as essentially fissures modified by sub-aerial agencies (Fig. 77), and the Duke of Argyle in 1868 engaged in a controversy with Geikie in which he endeavoured to

maintain a similar origin for the valleys of the Scottish Highlands. Nevertheless, the essential evidence, which proves that rivers excavate the valleys in which they flow, was perceived by Playfair in 1802, in presentation of the prescient, but then little known, work of Hutton. In his so-called Law of Accordant Junctions he emphasized the fact that tributaries (with a few readily explicable exceptions) join the main stream at exactly the appropriate level which, in modern terminology, implies their power to *grade* their courses to the level of their outfall (p. 162). It is, of course, recognized that a valley may be joint- or fault-guided, and that it may occupy, and become in effect coincident with, a major structural depression, but the power of running water to excavate a valley without tectonic guidance or advantage is now a truism.

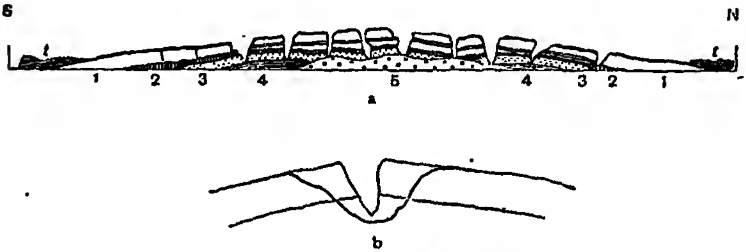


FIG. 77.—INITIATION OF WEALDEN VALLEYS ACCORDING TO LYELL.
(*a*) Longitudinal valleys. (*b*) Transverse valleys.

The general economy of river erosion.—A river, regarded simply as a mass of moving water has, in the final theoretical analysis, a certain amount of energy which depends upon its volume and its velocity. Its velocity depends partly upon the volume, but also upon the gradient and form of its channel. The total of energy is expended partly in overcoming friction and partly in the transportation of a load of debris.

The load of a river includes three distinct fractions: (*a*) the material in solution; (*b*) the suspended load, chiefly mud, silt, and sand; (*c*) the traction load, larger material carried along the bottom by a combination of rolling, sliding, and jumping movements. In the case of the Mississippi it has been computed that in the course of a year it carries to the sea 136 million tons of material in solution, 340 million tons of material in suspension, while the traction load is estimated at 40 million tons.

The power of active erosion possessed by a river is chiefly vested in its traction and suspended loads, which are, in other words, the essential tools in the process. Moving water without load exerts comparatively little erosive action, except in areas of soluble rocks where direct solution becomes a factor. The work of vertical or lateral cutting performed by a river in virtue of the abrasive power of its load is termed *corrasion*.[1] The power of corrasion of a river varies approximately as the square of its velocity. The general truth of this statement may be seen by considering that if the velocity be doubled, without any addition to the load, twice as many particles strike against any obstacle in a given interval of time and each strikes twice as hard. The corrasive effect is thus four times as great. The transporting power of a river increases very rapidly as the velocity increases ; it is generally regarded as proportional to the sixth power of the velocity. Neither of these generalizations should be regarded as having the validity of a mathematical law. They are approximations only, but they serve to indicate a principle of practical importance—the dominance of " flood erosion." A river performs far more work in corrasion and transport during a short phase of flood than during a lengthy period of normal conditions. This is often illustrated by the fact that the gullying action of torrential rains and cloud-bursts remains visible for long periods, in spite of the obliterating effect of normal weather conditions, acting more slowly.

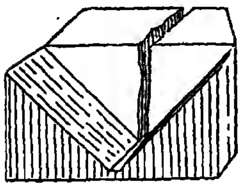
Moving air and moving ice are also capable of transporting a load, in virtue of which they are active eroding agents. The laws which govern their action are broadly analogous to those which operate in water erosion ; they have been less clearly formulated, however, and are the subject of some debate. It should be noted that in all parts of the field of study the geomorphologist (as distinct from the physical geologist) finds it better to concentrate on land-forms rather than processes, arguing thus from the effects to the causes which produce them.

[1] This process should be distinguished from *corrosion*—a purely chemical process.

CHAPTER XII

THE FORM OF WATER-ERODED VALLEYS

THE character of the transverse and longitudinal profiles [1] of valleys is an important factor in determining the nature of relief and the aspect of landscape. In order to trace the process of valley excavation completely it is necessary to assume an initial sloping surface. The methods by which such a surface are provided in nature need not for the moment concern us. Very violent falls of rain can, under certain circumstances, pass down a slope as a "sheet-flood" without concentration into definite channels (p. 305). We are entitled to assume, however, that the initial surface will commonly be sufficiently irregular to determine the courses as well as the direction of newly initiated streams.

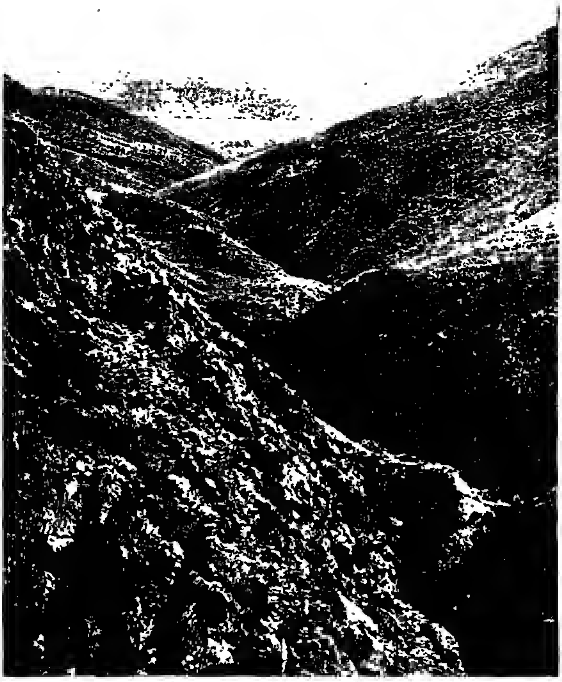


[*After Cotton.*

FIG. 78.—THE DIAGRAM SHOWS THE AMOUNT OF MATERIAL REMOVED BY VERTICAL CORRASION AND VALLEY WIDENING RESPECTIVELY.

The cross-profile of valleys.—The primary process in valley formation is vertical corrasion or down-cutting, and where this process alone is operative a gorge-like valley is produced. In such a case the process of deepening is dominant over widening, but under normal conditions of climate, widening by means of slipping, rainwash, and gullying will also take place, and will open the gorge into a V-shaped valley. Fig. 78 shows that a much greater amount of material is removed by the widening process than by direct downward corrasion. In the earlier stages of the history of a stream, down-cutting normally proceeds rapidly. Since tributaries are few and the valley slopes are not as yet extensive, the supply of debris tends to be small. A very important part of the vertical corrasion is, under these circumstances, performed through the localized drill-like action of pot-hole formation, in which angular debris is swirled round in an

[1] For the sake of brevity the terms *cross-profile* and *long-profile* are used in later pages. For the latter the term "thalweg" has commonly been employed, though such a use is hardly in accordance with its literal meaning "valley-way."



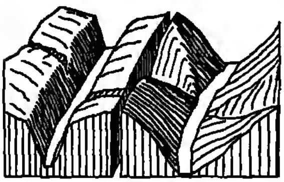
[Photo by H.M. Geol. Survey. Crown copyright reserved.

FIG. 79.—CROSSDALE BECK, ENNERDALE, CUMBERLAND, A TYPICAL STEEP-SIDED YOUNG VALLEY WITH OVERLAPPING SPURS.

[Photo by H.M. Geol. Survey. Crown copyright reserved.

FIG. 80.—POTHOLES EXCAVATED IN SANDSTONE IN THE BED OF THE RIVER GELT, NEAR BRAMPTON, CUMBERLAND.

eddy, excavating a cylindrical hollow and becoming rounded in the process. This manner of excavation is to be contrasted with the uniform, rasping or file-like, action of a stream in a later stage of life, possessing a larger load. Owing to the rapidity of down-cutting, young streams generally flow in steep-sided valleys, approximating in form to a gorge or narrow V (Fig. 81). In due course a stage is reached at which down-cutting becomes relatively slow. The widening processes, however, continue to act, and the valley thus becomes increasingly open in profile. The stage of evolution is thus legible to some extent in the cross-section of a valley, which passes through successive phases of form, the widening process overhauling the deepening process with the passage of time (Fig. 82).



[After Davis.

Fig. 81.—Stages in the Widening of a Young Valley.

When down-cutting slackens, the river may still possess an excess of energy above that necessary for the transport

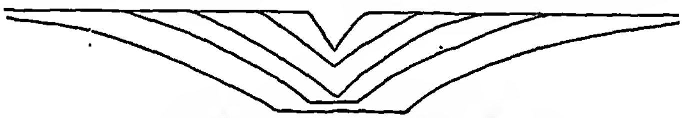
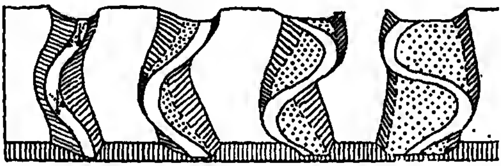


Fig. 82.—Stages in the Development of a Valley.

of its debris. This is expended in lateral corrasion, or widening of the valley floor. This process of lateral corrasion may be regarded as beginning even during active down-cutting. The initial course of the stream will be slightly curved in places, owing to irregularities in the surface, and lateral corrasion will constantly tend to enlarge the curves, under-cutting on the concave side of the valley, against which the fastest current impinges. In this way a series of meanders comes into being, separated by overlapping or interlocking spurs. The spurs have a gently sloping crest line or *slip-off slope*, while opposite to each is a steeply cut "*river-cliff*" (Fig. 83). The increase in the curvature of meanders may be regarded as continuing while down-cutting is in active progress. If it continues beyond this stage, widening of the valley floor must result. The stream will continue to corrade actively at the foot of the concave river-cliffs, which constantly recede, and a strip of flat ground, covered only in time of

flood, begins to appear round the bases of the spurs. The spurs themselves are also cut into by corrasion on the up-stream side, and become asymmetrical in profile, their steeper slope facing up-stream. In an actively corrading stream, the blunt, rounded terminations of the spurs which persist throughout the period of down-cutting become sharpened by this process, and they may ultimately be cut away altogether (Fig. 83). When this stage is reached, the valley possesses a wide flat floor, bounded by steep cliffs on either side. This level plain is the flood-plain of the river. When newly developed it will be coincident in width with the "meander belt" of the stream, but the meanders may still increase in size and corrade the base of the bordering bluffs where they are in contact with them. Thus the flood-plain grows and may come largely to exceed the width of the meander belt. The meanders unchecked by rock-spurs move actively down-stream, completing the planation of the



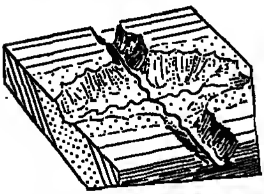
[After Cotton.

FIG. 83.—VALLEY FLOOR WIDENING BY LATERAL CORRASION.

valley floor. Lateral corrasion is thus a third process which, co-operating with deepening and widening, causes a regular progression in form in a valley undergoing excavation.

The concept of valley form as dependent upon "stage" has proved very fruitful in morphological studies, and is applicable also to many other land-forms. Assuming that the valley is excavated in homogeneous rocks, its profile depends upon the *stage* of evolution reached and the nature of the dominant *process* concerned in the excavation. But, as we have seen, process, whether deepening, widening, or lateral corrasion, is largely, though not entirely, a function of stage. Special circumstances may disturb the normal relations between the processes. For instance, in the absence of an adequate rainfall, the widening processes may be held in abeyance, and a valley may thus retain its youthful form for an unusually long period. The Grand Canyon of the Colorado River, 300 miles long

and locally more than a mile in depth, is a case in point. The river is fed by rains in its headwater region, but on its way to the sea it traverses a wide arid tract, the Arizona desert, and it is here that the canyon occurs. Special processes may become factors in other cases. Valleys cut in chalk and other limestones, where solution as well as corrasion plays a part, have a wide rounded form which differs from that of the true water-cut V (Fig. 128*c*).



[*After Cotton.*

FIG. 84.—VARYING CROSS-PROFILE OF VALLEY IN HARD AND SOFT ROCKS.

More important variations from the form imposed upon a valley by the joint control of process and stage depend upon the *structure* of the rocks through which a valley is cut. In this connexion we must regard structure as including not only geological structure in the narrower sense, viz. the disposition or attitude of the rocks, but also their hardness, texture, and the number and nature of divisional planes, such as joints, which cut them. It is sufficiently obvious that the profile of a valley will become open more rapidly in soft rocks than in

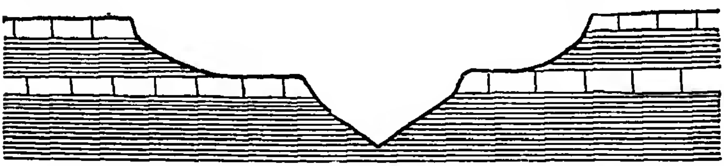


FIG. 85.—CROSS-PROFILE OF A VALLEY SHOWING STRUCTURAL ROCK BENCHES.

hard rocks. This emphasizes the fact that profile gives a measure of stage—not of actual age—since in the same valley we may find steep-sided and open portions coinciding respectively with terrains of hard and soft rocks (Fig. 84).

Again, during youthful stages, differential erosion of hard and soft rock bands will lead to irregularity and diversity in valley profile. Bedded rocks, consisting of alternate hard and soft strata, and disposed more or less horizontally, commonly give rise to structural rock benches determined by the outcrop of the harder bands (Fig. 85). Such benches must be carefully distinguished from alluvial terraces (p. 222); they are not directly related to the river in any way and do not, necessarily, fall in level downstream. A common, and more important, control

of valley form by structure is seen where rocks are inclined transversely to the valley direction, *i.e.* where the valley follows the line of the geological strike. In this case the cross-profile is asymmetrical (Fig. 86), for the stream has a constant tendency imposed upon it by the dip of the strata to cut sideways as well as downwards. In some cases it has gradually worked down the dip-slope of some hard stratum in the series, but this is not an essential feature in the process. Even in soft, relatively homogeneous rocks such as the London Clay, the tendency for asymmetrical development controlled by the dip is obvious, as is well illustrated by the Lea Valley north of London. This general process of asymmetrical development is called *uniclinal shifting.*[1] Other good examples are afforded

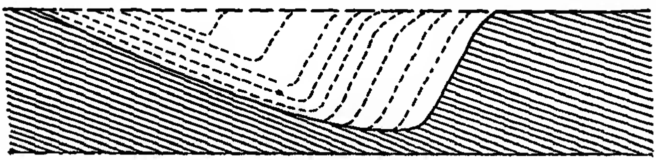


FIG. 86.—UNICLINAL SHIFTING.
Dotted lines show stages of valley excavation.

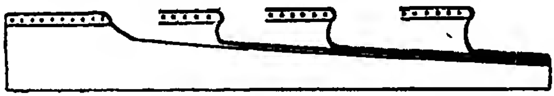
by the Thames Valley at Radley and the Cheddar Gorge. The feature is, in fact, of widespread occurrence, and is to be expected wherever a valley runs parallel with the general geological grain of the country. (See also p. 227.)

The long-profile of valleys.—The original gradient of a stream must necessarily be determined by the slope of the initial surface. If erosion were everywhere equal the slope would remain the same, and if the original surface were fairly flat, the long-profile of the stream would appear practically as a straight line. However, equality of erosion throughout the course cannot be attained in practice. Near the sea, the amount of down-cutting is limited by the proximity of sea-level, since the course of the river cannot be cut appreciably below it. Near the head, the down-cutting powers of the stream are limited by its small volume. Between these two extremes,

[1] The work "uniclinal," implying a uniform dip in one direction, is preferable to "monoclinal," since the asymmetrical development of valleys bears no necessary relation to "monoclines" in the geological sense (p. 105), although monoclines may, of course, be responsible for giving rise to the effect of uniclinal shifting locally.

somewhere in the middle course of the stream, the down-cutting will be greatest, and hence it results that at an early stage a rough concave profile is developed.

During the earlier stages of active down-cutting, differential corrasion between rocks of varying hardness gives rise to many irregularities of gradient, falls, rapids, etc. Some falls and rapids may, indeed, be due to original irregularities of gradient, as for instance, where the river course crosses a fault-scarp (p. 98) developed during the initial uplift. Such features are ephemeral, however, quickly disappearing as river erosion proceeds. Those which result from inequality of downward corrasion are longer lived and more important, though ultimately they, too, vanish as the work of smoothing of gradient proceeds. The crossing of a geological boundary, separating harder rock upstream from softer rock downstream, always gives



[*After Davis.*

FIG. 87.—STAGES IN THE RECESSION OF A WATERFALL.

rise to steepening of gradient, since the softer rock is more easily removed ; and, if the boundary plane is horizontal, or gently inclined upstream, falls normally result (Fig. 87), this condition being realized in the Niagara Falls, where the hard, sill-like mass of the Niagara Limestone overlies the soft Niagara Shales. A fall so constituted is liable to constant recession, since the harder rock above the fall is subject to persistent undermining by the powerful swirl and eddy action which wears away the softer rock at its foot. In this fashion a gorge arises, and it grows at a much faster rate than a gorge cut by simple vertical corrasion.[1] With the recession of the fall upstream its height decreases, because the beds are dipping gently upstream, and it must ultimately disappear (Fig. 87). Where the boundary plane of the contiguous rock masses is vertical, or steeply inclined, descent in a series of rapids is more usual than a true fall and a similar effect is produced

[1] In the case of the Niagara Falls the rate of recession of the Canadian Fall has been estimated variously as from 1 to 5 feet per annum. It is agreed that the American Fall has been receding more slowly. The gorge is now 7 miles long and assuming a rate of recession of 5 feet per annum this would have taken 7,000 years to excavate. The actual period was probably considerably in excess of this.

where the rock-junction dips downstream at a moderate angle. Shallow lakes constitute another type of irregularity in the gradient of a youthful stream. These, too, have an ephemeral existence, since they are inevitably drained by the lowering of their outlet in the course of down-cutting.

At the end of a sufficient period of undisturbed conditions a river will succeed in removing all the irregularities in its course, and will tend to a state of equilibrium with a relatively smooth course from source to sea (Fig. 88). In such a state a river is said to be *graded,* or at grade. The graded condition is one of exceedingly delicate balance. It implies that at every point on its course the total energy of the river is just sufficient to transport the available load. The bearing of the matter can best be seen by considering the result of a temporary departure from grade. If, for instance, the supply of debris slackens, an excess of energy will become available for down-

[*After* Cotton.

FIG. 88.—THE GRADED CURVE OF WATER-EROSION.

cutting. Corrasion or *degradation* will therefore begin, and this has the double result of reducing the slope, and hence the energy, and augmenting the supply of debris, both of which tend to re-establish the graded state. On the other hand, if the supply of debris is increased it is no longer possible for the river to transport it all. Some of it will be deposited (*aggradation*) in such a manner as to steepen the slope, increase the energy, and thus enable the river to cope with its larger load. In these two cases variation of load alone has been considered ; the energy of the river may be altered by other means, such as a change in gradient or volume. In all cases, however, the result is the same ; a train of adjustments is set in operation which combine to bring back the load and the energy to a state of equality. No river ever becomes exactly graded in the strict theoretical sense, and were this condition reached it would soon be disturbed by a change in one of the constantly varying factors which control it. Grade is to be regarded as a condition of equilibrium

6

towards which a river constantly tends. In practice, even when a river has closely approached the state of true grading, it oscillates on either side of the state of equilibrium. Nevertheless, many streams approach the ideal condition so nearly that they may be spoken of as graded, in the broad sense in which the term is generally used. The concave graded curve or "profile of equilibrium" is a fundamental and readily recognized unit in the architecture of landscape.

¶. **The profile of equilibrium.**—It is necessary to consider very carefully the implications of the conception of a profile of equilibrium and, in particular, to avoid certain erroneous deductions which have been based on it.

As already noted, sea-level acts as a *base-level* of erosion with reference to which the grading of the river takes place. It is, in fact, the fundamental base-level which controls the whole process of water-denudation on the land. Similarly, the point of confluence of a tributary with the main stream is a local base-level in relation to the grading of the tributary. Evidently, neither sea-level nor the levels of confluence points are fixed and immutable over long periods of time, but for short periods they represent the limit of "terminal" down-cutting, *i.e.* down-cutting at the mouth of the water-course.

Before general grading is attained, temporary local base-levels may be effective over parts of a stream course. Thus, where mountain streams collect in a lake which discharges their combined waters in one outflowing stream, the lake-level acts as base-level for the head-water streams, until such time as the lake is drained by down-cutting of the outlet or silted up by the growth and confluence of deltas. Again, a series of resistant strata or massive, poorly jointed portions of one rock mass may retard down-cutting, and modify the profile of a stream course in youth, by acting as local base-levels, each at the lower end of a temporarily graded reach (Fig. 89). Such base-levels inevitably cease to function as the development of the river proceeds; the several graded reaches tend to give place to one smooth curve which, however, is not necessarily regular or simple in form.

It will be readily seen that in all cases the graded curve will be first attained near the mouth or base-level point, for here the amount of necessary down-cutting is least. With the progress of time it proceeds backwards, *i.e.* headwards, from the lowest point. The grading of a stream course thus involves ***headward erosion.***

We may next inquire into the probable form of graded river curves and, to clear the issue of certain misconceptions, we shall do well to recall the history of development of ideas on this subject. As long ago as the seventeenth century it was recognized by Italian investigators, concerned with the regime of the Po and its tributaries, that the natural curve of water flow was concave upwards. Galileo believed it to be the arc of a circle; others preferred to regard it as a cycloid.[1] It should be noted, however, that the practical question bears little analogy to that of the form of "water-surface" in a regular channel, of which the frictional resistance is known or assumed. The latter problem is amenable to exact mathematical treatment; but the controlling conditions in actual river courses are too complex for quantitative definition. In 1697, Guglielmini announced conclusions in general terms

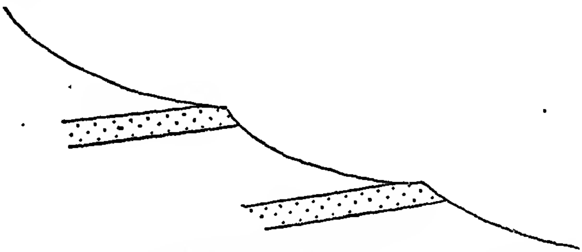


FIG. 89.—LOCAL BASE-LEVELS DUE TO RESISTANT ROCK MASSES.

which, in all essence, anticipated the concept of "grading," due to American physiographers nearly 200 years later. He laid it down clearly that rivers modify the form of their bed by erosion and deposition, in such fashion that equilibrium is attained between "force" and "resistance." It followed, therefore, that the grading of a river tends to be related to its velocity, its volume, and its load (in modern parlance). Moreover, not only is the total mass of the load involved, but so also is its size or "calibre." Fine-grained material is more easily moved, and therefore requires a flatter slope than coarse material.

If these principles be accepted, certain practical considerations at once emerge. An actual graded river curve could only flatten regularly downstream if its volume and mass and calibre of load underwent regular progressive change in the same direction. Such a condition cannot,

[1] A cycloid is the curve traced by a point on the radius of a circle as the circle rolls along a straight line.

in practice, be realized, and we should clearly expect the entrance of tributaries to cause some break of slope. If the channel is enlarged below the confluence, without proportionate increase in the quantity or calibre of load, the gradient should flatten; if, on the contrary, large quantities of coarse debris were supplied by the tributary a steepening of gradient should result.

It is further obvious that, even over a relatively short period of time, the river is tending to a number of distinct equilibria, appropriate to its varying volumes or levels. The load and volume conditions at low-water may be very different from those of flood. We note, however, that the efficacy of the river in tending to shape a profile of equilibrium is greatest at time of flood, when erosive and transporting powers are largely enhanced. Therefore, the actual curve at any time will be related most closely to flood conditions over the preceding period, and we may best reconstruct it by taking levels on the flood-plain along the river course, not of the water-surface in the channel.

In the light of these considerations we see that not only may actual profiles differ in varying degree from the profile of equilibrium, but that the latter, if developed, will be of a relatively complex form, which may defy simple mathematical expression. It is true, as the sequel will show, that portions of actual river curves can be expressed approximately by empirical mathematical formulæ (p. 166), but there is danger in associating the graded curve with a definite mathematical form. It has been asserted in some quarters that the curves of main rivers are tangent to sea-level. In a rough sense this is no doubt true, but it is not an exact relation, for recent movements of sea-level have drowned the mouths of all, or most, of the major rivers of the world, and subsequently there has not been time for complete grading to the new level. It is demonstrably *not* true that tributary curves are tangent to the curve for the main river. Each tributary represents an equilibrium appropriate to the volume-load conditions of the particular stream, and it is related to the main stream only to the extent that the point of confluence fixes the locally effective base-level.

Since it is impossible to associate any rigid form with the condition of grading, the question inevitably arises—how is this condition to be recognized? Consideration will show that the only practical method is to demonstrate

that neither aggradation nor degradation is in progress. This cannot be done by examination of the stream itself, but it is, nevertheless, possible to see whether it has recently trenched itself in its flood-plain, or shows any signs of recent upbuilding. In practice, the problem rarely arises in this simple and direct form, for recent changes of base-level have thrown most rivers out of adjustment, and the existing curves are composite (p. 221). We are therefore, in general, looking not for evidence of the graded state but for evidence of *regrading in progress.*

Lastly, let us note and avoid a serious error made by certain European physiographers in the nineteenth century. Basing their thinking on the earlier Italian work, which took a "short period" or engineering view-point, they attempted to carry over rigid pseudo-mathematical conclusions into the vastly different field of geological time-dimensions. They thus reached the astonishing conclusion that with the first attainment of equilibrium all downward erosion ceased. The curve in their view

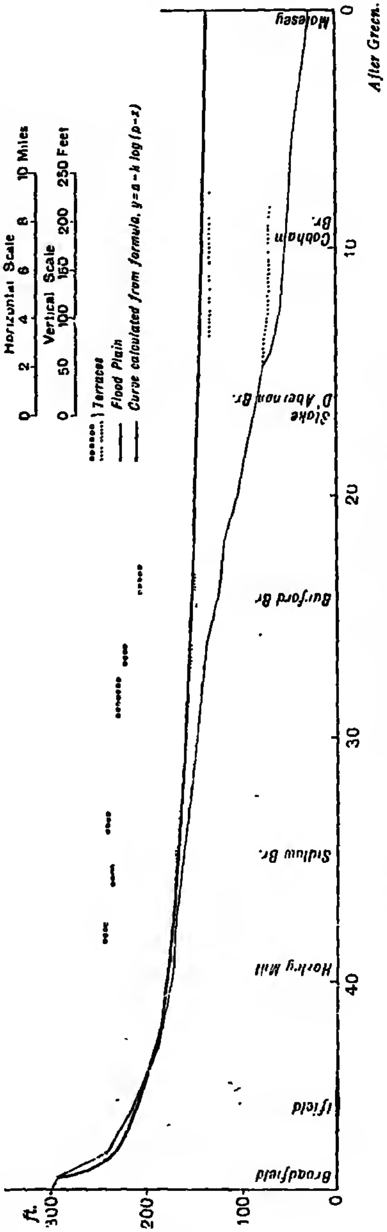


FIG. 90.—THE LONG-PROFILE OF THE RIVER MOLE, SURREY.

marked the theoretical limit of erosion, and by a combination of such curves we could envisage the final land-surface produced by denudation. This conclusion is utterly false. The slope of graded streams must inevitably change with the passage of time, since both the mass and calibre of the load and the volume of the stream must themselves change. For instance, at an early stage the stream will be transporting coarse debris down a steep slope, while in later life it will be carrying finer debris down a flatter graded slope. Major changes in volume and load will, in general, supervene gradually, and we are entitled to assume, in the theoretical analysis, that a stream once graded will remain graded, or at least that it will tend continually after the new equilibria demanded by the slowly changing conditions. In so doing, it will present, over a period of time, many different graded curves, the later members becoming progressively flatter in form. We cannot predicate any condition in which vertical corrasion completely ceases.

The mathematical form of river curves.—Though it is misleading to attempt to *deduce* the mathematical form of river curves from general considerations and definitely wrong to suppose that they tend to any *fixed* form, it is legitimate to inquire what type of mathematical expression best fits actual river curves. In this connexion some very suggestive results have been obtained by J. F. N. Green. He has shown that the curve for the upper part of the River Mole [1] (Fig. 90) accords closely with that of a calculated curve of simple logarithmic form, represented by an expression of the type :

$$y = a - k\log(p - x)$$

where y is the height in feet of a point above O.D., x its distance in miles from a point near the mouth, p the total length in miles of the stream,[2] and a and k are constants ; for the Mole curve they have the values 241·5 and 65 respectively. A curve of the same type also fits approximately the profile of other rivers such as the Wey, Dart, and Otter.

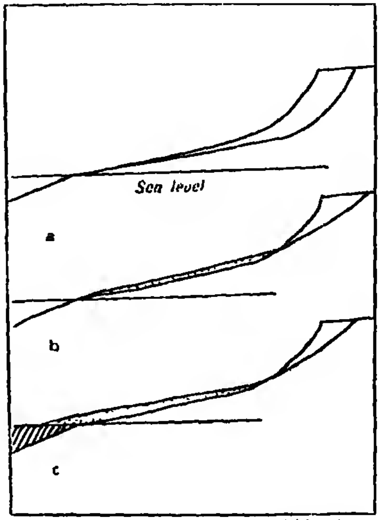
Particular significance attaches to the coefficient k in the above expression. It is proportional to the greatest

[1] The lower portion is excluded, since it involves portions of other curves, produced in later phases of grading to other base-levels (p. 221).

[2] In theory, the point a distance p from the mouth is the asymptotic point at which the curve becomes vertical.

curvature of the profile and may be termed the parameter of the curve.

If we calculate the change in form of the Upper Mole curve, accompanying headward erosion or a " cut-back " to the extent of one mile, with unchanged position of mouth, and a fixed parameter, we find that the amount of down-cutting would be almost negligible in the lower reaches; some 5 inches at 20 miles from the mouth, 2 feet 6 inches at 40 miles from the mouth, but over 60 feet near the head; 48 miles from the mouth (Fig. 91). The conditions here represented are unlikely, however. It is evident that as a river curve develops from a course, assumed initially linear in profile, the curvature, initially zero, increases. If the parameter thus increases as the river cuts back, the disproportion between down-cutting at the head and in the lower course increases, and if the parameter increases faster than the distance between head and mouth the second curve rises above the first in the lower course, implying aggradation. Green has calculated that if, during a one mile " cut-back " on the Mole curve, the parameter increases from 65 to 70, aggradation would ensue over about seven-eighths of the course, with a maximum thickness (less than 1 foot) some 34 miles from the mouth (Fig. 91). In this, as in the first-mentioned case, the mouth is assumed to be fixed in position, but a frequent result of back-cutting in such a case would be delta formation, whether in an estuary or off-shore, *i.e.* a definite lengthening of the course. This would lead to much more considerable aggradation. If, in the case of the Mole, 1 mile of headward erosion corresponded to 5 miles extension of course with delta growth, and the parameter remained unchanged, there would ensue nearly



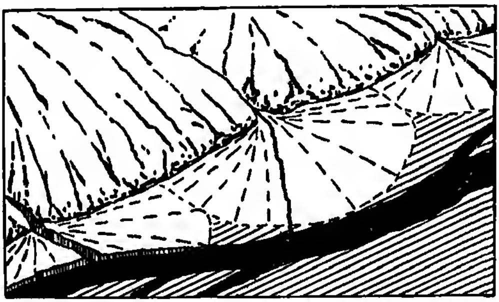
[*After Green.*

FIG. 91.—DEVELOPMENT OF RIVER-PROFILE UNDER DIFFERENT POSTULATED CONDITIONS.

(*a*) Parameter and mouth unchanged. (*b*) Increasing parameter; mouth unchanged. (*c*) Mouth advanced by delta.

3 feet of aggradation at the former mouth, diminishing upstream, for 40 miles (Fig. 91). With an increasing parameter, the effect would be more marked. If we consider a larger river, such as the Thames, for which Green suggests that the parameter might be of the order of 500, much larger aggradation figures would result. If for an initial course 100 miles long, 10 miles of back-cutting gave 30 miles of forward delta building, aggradation would extend for 105 miles up the new course of 140 miles, attaining a thickness of 38 feet near the earlier mouth.

Rightly understood, the results of Green's calculations are of great interest and importance. It cannot be asserted that all rivers must necessarily behave in the fashion deduced. If we assume, however, that rivers produce profiles of the above simple logarithmic type, and



[*After Cotton.*

FIG. 92.—ALLUVIAL CONES.

if during progressive change of form the profile remains of the same mathematical type, then erosion and deposition of the character indicated must inevitably ensue. Undoubtedly, the most significant principle emphasized by Green's discussion is, that under the conditions postulated, degradation and aggradation are not separate and successive processes, but related integral parts of one process of profile shaping. In any given phase of extension or headward erosion, marked down-cutting will be concentrated near the head of the stream, while deposition occurs in the middle and lower course. It is particularly to be noted that such deposition takes place without change of base-level, or climate. These principles are implicit in the general qualitative discussion of " grade " (p. 162), but Green's investigation gives them clarity and point, and enables us, further, to form some quantitative

estimate of the correlated amounts of erosion and deposition.

The question inevitably arises : How far are the above conclusions of general application ? An answer can be given only by confronting the deductions with the facts of observation. The task is complicated by the fact that changes of base-level, and of climate, have in fact occurred

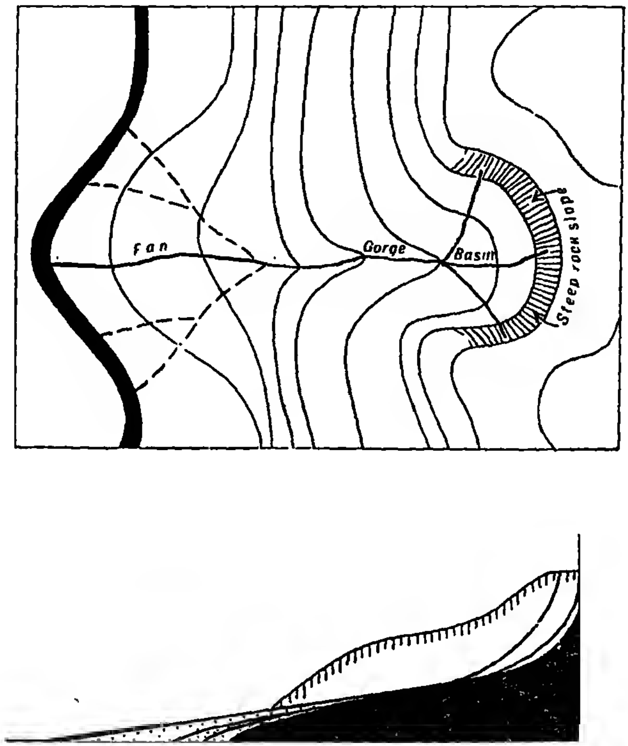
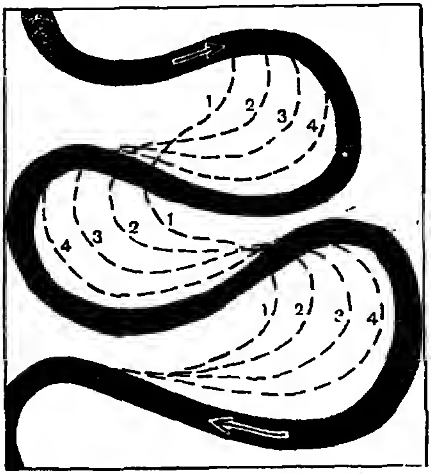


FIG. 93.—CONTOURED MAP AND SECTION OF AN ALPINE TORRENT.

during the shaping of the larger existing valleys, so that the observed facts of aggradation correspond with more complicated conditions than those envisaged above. The simple laws of river erosion and deposition are, however, admirably illustrated by the Alpine torrents studied by Surell as long ago as 1841. These torrents, descending into the major valleys—steep-sided glaciated troughs—have shaped their course in large part since the last glaciation, without radical change in local base-level or

climate. About their upper course is the half-funnel shaped *basin de reception*, while their lower course is across the surface of a *cône de déjection* (alluvial cone or fan) (Fig. 92). The profile evidently develops in fashion closely analogous to that deduced by Green (Fig. 93).



[After Davis.

FIG. 94.—DEVELOPMENT AND DOWN-STREAM "SWEEP" OF MEANDERS.

Turning to the larger valleys of the world, and ignoring minor complications, we obtain a picture equally consistent with Green's hypothesis. In general, such valleys show the results of aggradation in their lower and middle courses, while in the upper courses degradation has been recently in progress and may be still continuing.

River deposition.—The precise mechanism of river deposition involves two distinct processes, each represented by its own type of deposit. We have seen that development of meanders by lateral corrasion leads to the development of a flat valley floor. Once this stage is achieved, the "sweep," or downstream motion of meanders, can proceed unchecked (Fig. 94). When deposition begins the coarser debris (river gravel) can only be laid down in or near the river-course. But over a period of time the river-course comes to occupy every possible position on the valley floor. Hence a sheet of river gravel can in time accumulate over the whole valley floor, by the combined processes of up-building and meander sweep.

If, at any stage, active aggradation by coarse debris ceases, intermittent flooding can spread finer-grained alluvia widely over the flood-plain. This is essentially a different process, inasmuch as each layer of deposit is contemporary over a wide area. Though the term "alluvium," in its widest sense, covers all river deposits, British usage distinguishes between "river gravel" and

"alluvium," restricting the latter term to fine-grained flood deposits.[1] While such alluvium is spread as an

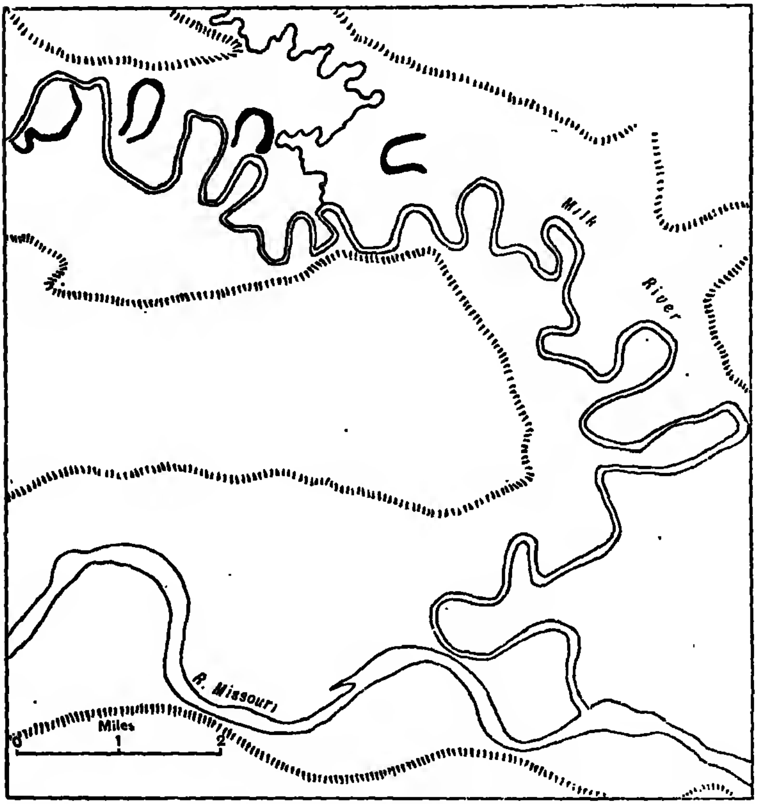
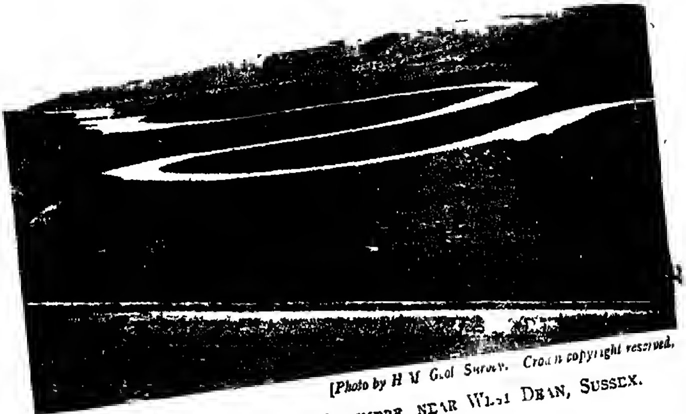


FIG. 95.—OX-BOW LAKES AND DEFERRED TRIBUTARY JUNCTION (MONTANA).

extensive sheet on the flood-plain, the bulk of the sediment is dropped near the river banks, thus building natural embankments or levees and rendering the transverse

[1] Generally speaking the present valley floors of the world show alluvium overlying river gravel. This points to a general change in conditions. In the recent past active aggradation by coarse debris was in progress, while in a still more recent period, extending into historical times, conditions of flood alluviation have prevailed. The comprehension of this change involves a consideration of the changes of base-level and of climate which have taken place since the maximum of the last Ice Age. The same difficulty confronts any attempted study of the simple conditions of river deposition. Briefly, we are restricted, in practice, to considering the valleys as they are, complicated by the many vicissitudes of the last and shortest period of geological history. We shall, therefore, return to the subject of river deposition on a later page (p. 423).



[Photo by H M Geol Survey. Crown copyright reserved.

FIG. 96.—MEANDERS IN RIVER CUCKMERE, NEAR WEST DEAN, SUSSEX.

[Photo by A. J. Bull

FIG. 97.—THE ALLUVIAL FLOOD-PLAIN OF THE RIVER ARUN, NEAR AMBERLEY, SUSSEX.

profile of the flood-plain slightly convex. The effect is prominent in the lower parts of the Mississippi, where, originally, natural embankments, several hundred feet in width, served to impound the waters of moderate floods. In such circumstances, a break through or overflow causes diastrous flooding in the lower-lying " back-lands." Attempts to raise and strengthen the natural levees by artificial means are rarely successful in the long run, since they confine the flood current too narrowly and often precipitate the disasters they are designed to prevent.

Flood alluviation, like aggradation by gravel, is closely linked with the development of meanders. Flood alluvium presents no considerable resistance to the growth and movement of meanders, and the short-circuiting and abandonment of meander loops in time of flood is a frequent occurrence on flood-plains. The abandoned loops form " cut-offs," " ox-bows " or " mortlakes " which, in time, become silted up with flood detritus and the peaty residues of vegetation growing in the stagnant water (Fig. 95). It should be noted that artificial diversion of meanders has often been undertaken in the course of canalization or flood prevention works ; in many cases all that has been done is to hasten an imminent natural " cut-through."

A related effect is seen in the common phenomenon of " deferred tributary junctions " on flood-plains (Fig. 95). A tributary course is prolonged downstream parallel with the main river, its ultimate confluence occurring on the convex side of a major meander. It is evident, in such cases, that the mouth of the tributary has been drawn downstream in the course of meander sweep. A limit to the process is set by the approach of the next meander upstream, which will finally " capture " the tributary at a time of flood-overflow, leaving its former lower course abandoned.

CHAPTER XIII

THE CYCLE OF EROSION

The fundamental principles of the cycle of erosion.—In the foregoing paragraphs we have traced the evolution of a water-cut valley, treating it as a single isolated land-form. The method there employed, and the terminology adopted, may serve as a basis for the treatment of the development of other land-forms, and more particularly of a landscape, as a whole. A landscape has a definite life history during which it shows a series of gradual changes, whereby the *initial* forms pass through a series of *sequential* forms to an *ultimate* form. We may broadly group the many successive stages into the major stages of *youth*, *maturity*, and *old age*. Landscape evolution is thus envisaged as a cycle which runs through a definite course of development. Thus, starting with the simplest case, a newly uplifted sea-floor, it is possible to make out deductively the successive phases of relief which ensue from the operation of erosion. We trace first the appearance of relief from an initially featureless surface; its growth to a maximum as the valleys are deepened; and its slow, but inevitable, obliteration as the ridges are lowered, with the final production of another surface of low relief. The recognition of the possibility of such eventual obliteration of relief or planation is, perhaps, the first and most fundamental principle of the cycle of erosion. It proved, in fact, the starting point of the fertile lines of study reviewed in the following pages.

It is, therefore, clearly of prime importance to recognize the *stage* of evolution attained in landscape development. But as in the case of a single valley, the *process* of sculpture stamps its character on the country, while rock characters, conveniently summed up under the term "structure," are also potent factors in determining form. We may say, then, following W. M. Davis, that "landscape is a function of *structure*, *process* and *stage*."

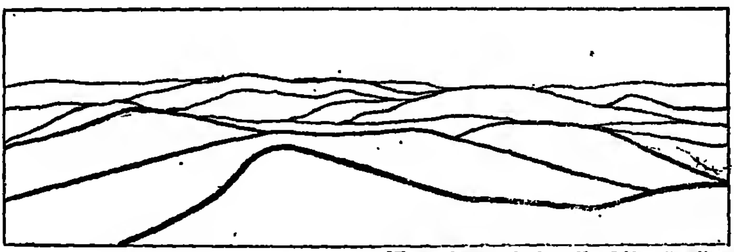
We are primarily concerned, for the moment, with the cycle of normal erosion, *i.e.* erosion under the control of normal river action. The conception of the cycle may evidently be extended in some measure to cover the cases

of "arid" and "glacial" erosion; and it proves eminently applicable to the study of marine erosion. Such applications are discussed in the sequel.

The initial surface which forms the starting point of a cycle of erosion may be of very varied forms and structures. The simplest case is afforded by the uplift of new land from beneath the sea. We shall make the further simplifying assumption that the uplift is rapid, so that there [illegible] time for any significant amount of erosion [illegible]

FIG. 98.—STAGES IN CYCLE OF EROSION.

progress. The new land-surface will possess an initial relief, due to original inequalities or deformation during uplift. The first streams will show some relation to such inequalities, but their courses will be, primarily, consequent upon the broader, original or constructional slopes of the surface. Such streams are known as *consequent streams*, and we may envisage the excavation of a series of consequent valleys as the first stage of the cycle. The characters of the valleys as they develop, stage by stage,



[*From photograph of the Blue Ridge, Carolina.*

FIG. 99.—A MATURELY DISSECTED UPLAND.

have already been reviewed. It remains to trace the evolution of the landscape as a whole.

The interstream areas or *interfluves* will at first be broad flat-topped ridges retaining on their summits extensive tracts of the initial surface (Fig. 98). The progress of valley-widening narrows the interfluves and, continuing after active down-cutting has ceased, must eventually destroy the last surviving traces of the initial surface. This is a critical point in the development of the relief, and one which is readily recognized on the ground (Fig. 99).

CHAPTER XIII

THE CYCLE OF EROSION

The fundamental principles of the cycle of erosion.—In the foregoing paragraphs we have traced the evolution of a water-cut valley, treating it as a single isolated land-form. The method there employed, and the terminology adopted, may serve as a basis for the treatment of the development of other land-forms, and more particularly of a landscape, as a whole. A landscape has a definite life history during which it shows a series of gradual changes, whereby the *initial* forms pass through a series of *sequential* forms to an *ultimate* form. We may broadly group the many successive stages into the major stages of *youth*, *maturity*, and *old age*. Landscape evolution is thus envisaged as a cycle which runs through a definite course of development. Thus, starting with the simplest case, a newly uplifted sea-floor, it is possible to make out deductively the successive phases of relief which ensue from the operation of erosion. We trace first the appearance of relief from an initially featureless surface; its growth to a maximum as the valleys are deepened; and its slow, but inevitable, obliteration as the ridges are lowered, with the final production of another surface of low relief. The recognition of the possibility of such eventual obliteration of relief or planation is, perhaps, the first and most fundamental principle of the cycle of erosion. It proved, in fact, the starting point of the fertile lines of study reviewed in the following pages.

It is, therefore, clearly of prime importance to recognize the *stage* of evolution attained in landscape development. But as in the case of a single valley, the *process* of sculpture stamps its character on the country, while rock characters, conveniently summed up under the term "structure," are also potent factors in determining form. We may say, then, following W. M. Davis, that "landscape is a function of *structure*, *process* and *stage*."

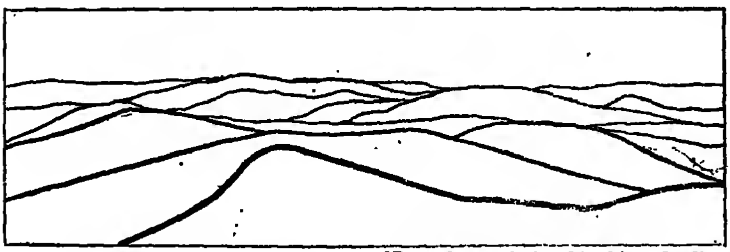
We are primarily concerned, for the moment, with the cycle of normal erosion, *i.e.* erosion under the control of normal river action. The conception of the cycle may evidently be extended in some measure to cover the cases

of " arid " and " glacial " erosion ; and it proves eminently applicable to the study of marine erosion. Such applications are discussed in the sequel.

The initial surface which forms the starting point of a cycle of erosion may be of very varied forms and structures. The simplest case is afforded by the uplift of new land from beneath the sea. We shall make the further simplifying assumption that the uplift is rapid, so that there [illegible] time for any significant amount of erosion [illegible] agent

FIG. 98.—STAGES IN CYCLE OF EROSION.

progress. The new land-surface will possess an initial relief, due to original inequalities or deformation during uplift. The first streams will show some relation to such inequalities, but their courses will be, primarily, consequent upon the broader, original or constructional slopes of the surface. Such streams are known as *consequent streams*, and we may envisage the excavation of a series of consequent valleys as the first stage of the cycle. The characters of the valleys as they develop, stage by stage,



[*From photograph of the Blue Ridge, Carolina.*

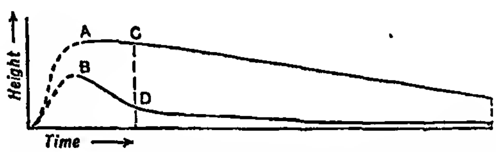
FIG. 99.—A MATURELY DISSECTED UPLAND.

have already been reviewed. It remains to trace the evolution of the landscape as a whole.

The interstream areas or *interfluves* will at first be broad flat-topped ridges retaining on their summits extensive tracts of the initial surface (Fig. 98). The progress of valley-widening narrows the interfluves and, continuing after active down-cutting has ceased, must eventually destroy the last surviving traces of the initial surface. This is a critical point in the development of the relief, and one which is readily recognized on the ground (Fig. 99).

shown by the divergence of the two curves on the graph. It reaches a maximum at, or just before, the beginning of maturity, when the last traces of the initial surface disappear. Thereafter, the ridges begin to diminish in height faster than the valley-bottoms are lowered, for vertical corrasion is on the wane. The two curves thus approach one another, representing diminishing relief. [illegible] of the cycle the convergence of the curves will slowly continue, but the process is immensely protracted, since erosion must decrease in intensity with the reduction of height and steepness of the hills. To complete the graph to scale, the theoretical ultimate-point of convergence would have to be placed far to the right of the edge of the page.

The relation between uplift and erosion.—A leading assumption made in the foregoing paragraphs, viz. that uplift is effectively complete before erosion begins,



[*After Davis.*

FIG. 101.—GRAPHICAL REPRESENTATION OF AN EROSION CYCLE. AB, Initial relief; CD, Maximum relief.

evidently simplifies the first presentation of the cycle concept, but we should clearly be mistaken in regarding it as a necessary or invariable relationship. In general, the cycle should not be regarded as beginning with the erosion of an already uplifted mass. Erosion and uplift inevitably overlap to some extent, and the cycle really begins with the first emergence of a sea-floor, or the first movement of deformation of a land-mass. We have seen that the whole tenor of research on the growth of structures (p. 90), emphasizes the early beginnings and long-continuance of earth-movements. The climax may supervene quickly, but the premonitory movements occupy a long period. We must, therefore, be prepared to envisage not only long-continued uplifts, but uplifts at varying rates. The simple conditions postulated above are not necessarily false in all cases. They represent not only possible, but various actual occurrences. However, alternative time relations between uplift and erosion must be examined and their consequences deduced.

Certain simple interactions of uplift and erosion may quite readily be conceived. Thus, very narrow, steep-sided young valleys may mark regions in which rapid elevation occurred concurrently with valley incision. This explanation should rank as a working hypothesis in dealing with canyon valleys. It involves an acceleration of valley deepening compared with valley widening, as against the hypothesis of suspension of valley widening through climatic causes. The famous Colorado Canyon occurs in a region of recent rapid uplift and probably owes its form as much to this as to the aridity of the region (p. 158). Conversely, valleys of open form, without flood-plains, would suggest slow uplift, such that, while valley deepening was not complete, slope grading had been able to keep pace with it. Such valleys, to quote W. M. Davis, " will, Minerva-like, begin life with maturity," the stage of youthful relief being suppressed.

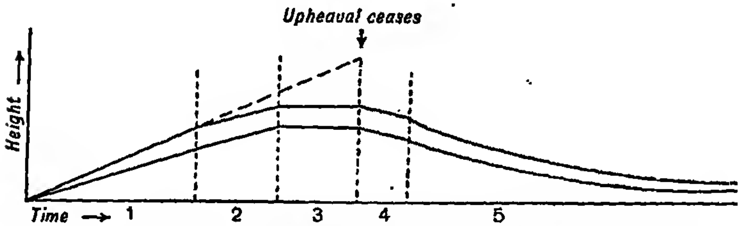


FIG. 102.—PENCK'S CONCEPTION OF A CYCLE OF EROSION DURING LONG-CONTINUED UPLIFT.

Upper and lower lines represent respectively ridge-crest and valley-bottoms.

It is to Penck that we owe the most elaborate and systematic examination of the consequences of long continued uplift in the cycle of erosion. He conceived an ideal cycle, in which a lowland was subject to broad upheaval into a dome, the uplift being fairly rapid and long continued. The successive stages in the evolution of relief are represented in Fig. 102. In Stage 1, the flat interfluves are little eroded and gain in altitude by the amount of the upheaval. Valley deepening, however, does not keep pace with the upheaval, so that both absolute altitude and relief increase. In Stage 2, the interfluves have become sharpened by valley widening, and, thereafter, are lowered as fast as the valleys are lowered (p. 177). They now gain in altitude more slowly, by the amount of uplift minus the amount of valley deepening. The latter still fails to keep pace with the

uplift, so, while the crest altitude increases, the relief remains constant. In Stage 3, the streams, still cutting down vigorously under the influence of continuous upheaval, deepen their valleys as fast as the uplift proceeds. The ridges are still lowered as fast as the valleys are deepened, so that both altitude and relief remain constant. In Stage 4, uplift has ceased ; valley deepening continues for a time, with concurrent reduction of the ridges; altitude begins to decrease, but relief still remains constant. Finally in Stage 5, the process of valley deepening slackens, the ridges become rounded and are progressively reduced, so that both relief and altitude slowly diminish.

In the same context, Penck briefly outlined two other ideal cycles. In one, with marked uplift of short duration, sharp-crested interfluves could not result, for valley deepening would not be able to go far enough in the early stages, when slopes were steep. The ridges would thus pass directly to the rounded condition. In the other, slow upheaval is envisaged, with the valleys deepened as fast as the land is raised and widened faster than they are deepened. This is essentially the condition noted above (p. 179). The flat-topped interfluves would be degraded as fast as they were raised, and sharp relief would never be attained.

In considering the general question of relation between upheaval and erosion, particularly in the light of Penck's first ideal cycle, there are several important points to be considered. The stages of this cycle are not to be regarded as in any sense "natural" or inevitable. They are possible, but they depend on a very special relation between rate of uplift and rate of degradation.[1] It is at least open to question, as Davis has contended, whether the relation could be realized under the stated conditions of the "experiment." Nevertheless, Penck's argument points to a *method* of deductive investigation of which the value is independent of particular applications. Evidently, we could vary the conditions still further by assuming a variable, instead of a constant, rate of uplift. The reader will find it worth while to reconstruct graphically further imaginary cases, varying the conditions as widely as possible. All such ideal cycles, however, are of little value until the deduced results are successfully matched

[1] To this extent Penck's scheme makes more numerous and, in some respects, more unlikely assumptions than the simpler scheme originally propounded by Davis, which it is designed to replace or extend.

with actual landscapes, for only thus can we assure ourselves that the imagined conditions are within the field of terrestrial possibility.

The most significant condition pictured by Penck is the balance between rate of upheaval and rate of valley deepening (and, therefore, of ridge lowering) in Stage 3. Penck believes that this condition was realized in the last phase of upheaval and sculpture of the Alps. Whether this be so or not, it is clear that such a condition is likely to occur in the central regions of uplift of a mountain range. We have seen (p. 84) that the last constructional act in mountain building is the broad up-arching of the folded mass, and it is likely that the movement of uplift lasts longest in the central regions. Penck's first ideal cycle may thus be applicable to the axial tracts of mountain regions, while conditions more akin to his second or third ideal cycles may hold in the marginal zones. On the other hand, where the total amount and, probably also, the duration of uplift was less, it is reasonable to assume that the conditions pictured in Fig. 101 were often realized. As evidence of the possibility and wide prevalence of such rapid short-lived uplift we may note the extensive survival of "flat-tops" on upland summits, suggesting the bodily hoisting of initial surfaces much faster than they have been consumed. In any case, it is true to say that the form of many regions outside the mountain zones is indistinguishable from the form they would have assumed under the conditions of Fig. 101, and that, as a rule, we must necessarily remain in ignorance of the exact introductory conditions of a cycle of erosion.

The modification of normal erosion by climate.—The scenic profiles of the middle stages of the cycle—the stages of strong relief—reflect, in large measure, the relation of valley deepening to valley widening, and this depends, in part, on the relation between uplift and erosion. It depends also on the general climatic conditions. Within the general climatic field of "normal erosion," which excludes only the hot and cold deserts and their border zones, there is sufficient differentiation of conditions to leave distinctive marks on the landscape. Broadly, we may distinguish in this connexion between the humid intertropical regions, the humid continental margins of temperate latitudes, and the sub-humid continental interior regions.

In the humid tropics observation shows that ridge-

crests tend to be sharp, and sharp conical hills abound, while the slopes show a tendency to be concave. The broad valleys may bear some resemblance to those of glaciated regions. Two factors are concerned in producing these results, viz. the heavy rainfall, and the intense chemical rotting of the rocks. The concavity of the hill-sides points to the prevalence of "wash" over soil-creep, such as might normally arise from excessive rainfall. There is, however, no doubt that land-slipping contributes to the results. From many observations we may select those of J. W. Evans, who noted that the Devonian calcareous sandstones of the Bolivian Andes were rotted to a friable and unstable condition on slopes. He observed further that the Palæozoic slates of the eastern slopes of the Cordillera Real were converted into a red slippery clay below 8,000 feet, and that "the weight of the altered rock becomes too great for its feeble coherence to sustain, when a great mass separates and makes its way down the slope in a *derrumbado* or landslip, leaving great reddish scars on the valley sides." It is significant that the trees of the tropical rain forests are shallow-rooted, and therefore less effective in binding the waste-mantle than those of temperate regions.

In the temperate regions we are concerned to trace any significant differences between the wetter and the drier regions of the rain climates, *i.e.* between the forest and the grassland regions. As regards the regions of natural forest, it has been contended in some quarters that a tree-cover greatly retards, or even inhibits, slope grading and the wasting of divides. As against this we may observe that forested ridges commonly present the convex profile which can only readily be explained by soil-creep. Moreover, in Western Europe at least, it may often be seen that the attitude of the roots and trunks of trees bears the clear impress of adjustment to downhill creep. That soil-creep is a slow process is not to be gainsaid, but there is no reason to doubt that, in the long run, it can catch up and keep pace with decelerating downward corrasion.

As regards the grasslands it is difficult to say how a turf-mat would compare with a tree and bush cover as a soil-binder *under equal conditions of rainfall*. Much, of course, depends on the floral constitution of the turf. In general, we should expect it to be less effective in resisting gullying, but the study of conditions in Britain suggests possible exceptions to this rule. On the broad scale, however, the grasslands show lower rainfall and higher evaporation than

the forestlands, and this is the significant fact for our purpose. It is probable that the wasting of divides by wash and soil-creep is relatively retarded in the grassland areas and that, in consequence, the production of valley flood-plains by lateral corrasion takes on a relatively more important role in the shaping of landscapes, maintaining steep bluffs at the bases of the very slowly wasting ridges. Such a condition appears to be common over large areas in Western North America.

On the semi-arid borders of the grassland zones entirely distinct processes contribute to the modification of profiles, notably the accumulation of the exported wind-blown dust of the deserts, which tends to level up inequalities. This, however, is a foretaste of "arid erosion," and involves conditions not proper to the "normal cycle."

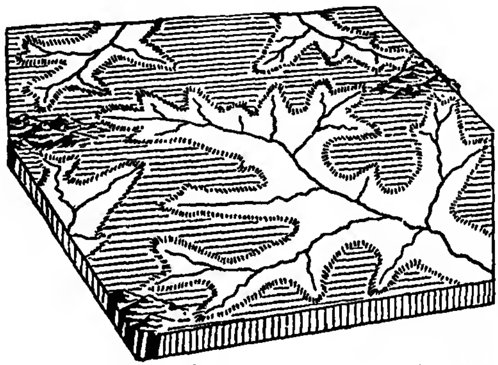
The late stages of the cycle of erosion.—Whatever variations are imported into the earlier stages of the cycle of erosion, by uplift history or climatic environment, the later stages must be closely similar in all cases. The forms produced and the precise processes at work, however, must necessarily be largely a subject for deduction, since the current cycle of erosion has produced old-age forms only locally, and over small areas. It is true that the ultimate forms of ancient cycles of erosion are preserved for our study in "hill-top planes," etc., but the method by which these former plains were produced is still in dispute.

In the orthodox presentation of the cycle of erosion, the later stages are represented as largely concerned with the gradual lowering of the interfluves by atmospheric wasting. This process is regarded as continuing long after active valley deepening has ceased, so that it tends to the obliteration of the strong relief of maturity, producing in the limit a rolling lowland, on which rivers flowing with gentle gradients are separated by low swells of the surface. For such a surface W. M. Davis proposed the term "peneplain." On the peneplain, thus conceived, differences of rock resistance would have ceased to exercise any general control on form. Nevertheless, local resistant masses, or tracts spared by an accident of "circum-denudation" might form residual hills, rising above the surface; the term "monadnock" from Mount Monadnock in New Hampshire has been adopted as a general name for such hills (Fig. 103).

It is evident that a peneplain formed in this manner would not be in any sense a level surface. It would

necessarily retain a slope towards the coastlines, and might stand relatively high above sea-level in the central parts of a large land-mass. It is equally clear that its production would require vast periods of time, since erosion would decrease progressively in intensity with the reduction of general relief. It has been estimated that North America would be completely "base-levelled" in some 15 million years if river erosion maintained its present rate. Allowing for the inevitable slowing down of the process, twice or three times this period would certainly be necessary.

In the light of these considerations, and of the known instability of the continents, some writers have argued that the cycle of erosion can never have run its full course, and



[After Cotton.

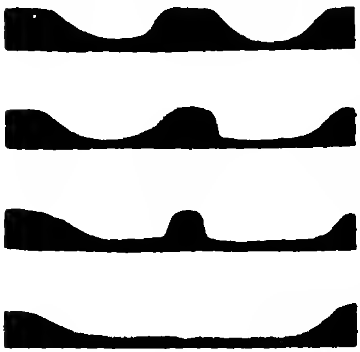
FIG. 103.—PENEPLAIN WITH MONADNOCKS.

that the "peneplain" is an unrealized and unrealizable abstraction. It is undoubtedly true that extensive low-lying peneplains, related to existing sea-level, are rare or absent on the present continents, but this argument can carry little weight when we remember that the lands are now in course of active degradation following geologically recent and recurrent uplifts. If we extend our scrutiny in point of time we can recognize surfaces of low relief, which may have been formed as peneplains, in two classes of situation : (*a*) uplifted so as to form plateau surfaces—or the summit planes of hills, (*b*) buried beneath later sediments and coinciding, therefore, with the planes of unconformity of the geologist. Denudation may partially exhume surfaces of the latter type from beneath their overburden of sediments and hence they may reappear as topographic forms in the landscape.

The existence of such surfaces enforces what we may regard as the fundamental principle of the cycle of erosion, viz. that relief can be entirely obliterated; but it by no means follows that the surfaces were ever peneplains in the sense defined above. Two other possibilities at least must be considered. In the first place, flat upland surfaces and planes of unconformity have been interpreted, particularly by British geologists, as plains of marine denudation, representing the ultimate product of wave attack upon the land. In such fashion, nearly a century ago, Ramsay explained the even skyline of the mountains of South Wales. Where marine deposits rest on a plane of unconformity, the ascription of a marine origin to the latter seems at first sight a natural conclusion. Counter arguments are not lacking, however. It has been urged that marine planation is slow when compared with sub-aerial levelling, acting simultaneously over the *whole* surface. In Geikie's words: "Before the sea, advancing at the rate of 10 feet per century, could pare off more than a mere marginal strip of land . . . the whole land might be washed into the ocean by atmospheric denudation." Again, as Davis has contended, "a slight movement of elevation usually sets the sea back to begin its work anew . . ., but such an elevation only accelerates the work of sub-aerial denudation. . . ." It is fair to add that D. W. Johnson, a leading authority on marine erosion, does not consider these arguments final. In particular the figures on which Geikie relied over-estimated the over-all rate of sub-aerial wasting by assuming a continuance of the *present* rate of river-erosion. The general tendency of recent work has been to justify the idea that, at least, some of the ancient surfaces of low relief are essentially plains of marine denudation. It must not be supposed, however, that a covering of marine deposits necessarily proves the marine origin of the surface on which they rest. In some cases the sea advanced across a land-surface already far advanced towards planation, and the waves finished, by a final "trimming," the work that sub-aerial agencies had already accomplished in essence.

Recently, C. H. Crickmay has launched a cogent attack on the conception of the peneplain from another angle. In his view the rate of wasting of divides has been over-estimated. It is demonstrably slow under certain existing conditions, and must become slower with diminishing relief. He believes, therefore, that planation by lateral corrasion,

which begins with the first grading of the streams and can continue long after active deepening has ceased, must assume a dominant role in the late stages of the erosion cycle, causing the prevalence of broad flood-plains, thinly veneered with sediment. He sites examples illustrative of the power of lateral planation in meander growth and migration, and states that the observation of flood-plain borders convinces him "that cliffs in these places are as nearly continuous as cliffs on sea-coasts," and that lateral erosion by streams is as important as wave erosion. Such lateral erosion would maintain relatively steep slopes on flood-plain borders till late in the cycle; and the aspect of a landscape so shaped would be very different from that of a peneplain.



[*After Salisbury.*

FIG. 104.—STAGES IN THE DESTRUCTION OF AN INTERFLUVE BY LATERAL CORRASION.

In the limit, he believes that the growing flood-plains would become confluent, giving a surface much flatter than that of a true peneplain, but with a general seaward slope. This would involve the paring away of interfluves (Fig. 104), of which, however, remnants might remain as monadnocks. For the final confluent flood-plain surface, he proposes the term *panplane*, analogous to "panfan" (p. 315). Finally, he sees no reason to assume any great slowing up of lateral corrasion in old age, so that on this theory it becomes possible to assume that panplanation can be achieved rapidly, by contrast with peneplanation.

Certain criticisms of Crickmay's theory have been offered elsewhere, and cannot be fully repeated here. It can hardly be doubted that he has made an important contribution to the theory of the erosion cycle, and it may be conceded as probable that many so-called upland peneplains of limited extent are in reality panplanes, and that in other cases the ultimate surfaces of sub-aerial degradation have been produced by a combination of peneplanation and panplanation. His case, however, is overstated if it is intended as a complete abrogation of the concept of peneplanation. Rolling landscapes of the peneplain type are demonstrably in existence over areas of weak rocks.

These are not, as Crickmay appears to suggest, curious exceptions to the general rule; they typify the potential conditions of the vast continental areas floored by the less coherent rocks. For these areas at least peneplanation is a valid concept. Again, it is probable that the relative advantage of lateral planation over general wasting of divides is greater in the sub-humid than the truly humid regions (p. 183). Moreover, all Crickmay's estimates of the relative rates of vertical and lateral corrasion and "wasting" are necessarily derived from present landscapes, most of them far removed from old age. In assessing the relative rates of processes with the passage of the cycle he is thus in the same difficulty as advocates of peneplanation. Such assessment is, in effect, extrapolation on a curve of unknown form, lending itself to personal judgment or assertion, but not to proof.

The conclusion of our discussion must be that erosion surfaces of low relief can arise in at least three ways: by simple peneplanation, by marine abrasion, or by panplanation. In many cases, an actual surface must arise from the co-operation of two or all of these processes. In so far as marine abrasion and lateral river corrasion alone produce surfaces, these surfaces will tend to be more nearly plane than a true peneplain surface.

The cycle concept in geomorphology.—The basic ideas of the cycle of erosion took their origin in the work of Powell, Gilbert and others in the first geological reconnaissance of the Western United States, during the latter half of the nineteenth century. These regions of simple structure and spectacular erosional land-forms, largely unconcealed by vegetation, were well adapted to evoke a realization of the fundamental laws of water-erosion. The systematic presentation of the scheme of the cycle was the work of W. M. Davis, and it is impossible to overestimate the debt of geomorphology to this pioneer and his followers. The compelling advantage of the viewpoint developed by these workers is that it affords the basis of a *genetic* classification and nomenclature for land-forms, in place of a morphological system. The equipment of simple descriptive or morphological terms available in older geographical literature is ridiculously inadequate,[1] while the more modern morphological systems devised

[1] See, for example, the terms listed and defined in Chapter V of *The International Geography*, edited by H. R. Mill.

by certain German workers are insufferably prolix and elaborate. A genetic nomenclature, such as arises from the cycle conception, affords a means of expressing the whole texture and build of a landscape in a few simple words. While the several associated land-forms do not march to their culmination in a rigid unison, they express significant harmonies. For example, to state that a region is maturely dissected implies a certain correlation between the form of its several parts.

Apart altogether from differences of opinion as to the balance of processes during the cycle, critics have not been wanting to deny its value as a general method or philosophy. To adopt the genetic viewpoint is to form a hypothesis of the whence and the whither of the landscape forms. Some have asserted a preference for a simple statement of what is there, without consideration of possible origins and ultimate state. We must leave the reader to judge whether this view is not needlessly narrow and unimaginative and calculated to retard, rather than advance, morphological study.

Again, the cycle has been misinterpreted as a rigid scheme, devised deductively without reference to the facts of nature, and one into which the latter have to be forced, if they will not naturally fit. On the contrary, it is a sort of mental scale of reference by which the actual facts of landscape are constantly compared. It has never been assumed that the cycle need necessarily run its full course ; the sequel will make clear certain of the actual complexities which arise under this head. Nor need it be supposed that the scheme and its nomenclature are incapable of extension and refinement. In its essential emphasis on ordered sequence, the cycle concept made a major contribution to geomorphology, which gave life to a dead subject. Land-forms, whether on the map, the ground, or merely glimpsed in passing from a railway carriage window, are seen in their true significance only if it be remembered that they have developed, and are developing.

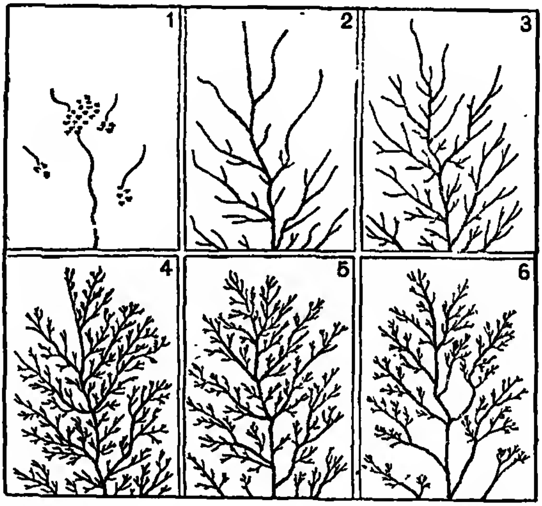
CHAPTER XIV

THE DEVELOPMENT OF DRAINAGE SYSTEMS AND ADJUSTMENT TO STRUCTURE

Tributary development.—In discussing the general course of the cycle of erosion we ignored, for the sake of simplicity, the closely related processes of tributary growth and "adjustment to structure," which, in fact, give much of the significant detail to water-sculptured landscape.

With a constructional slope of simple form we should expect the initial drainage plan to consist of sub-parallel consequent streams. We must allow also for cases in which the form of the initial surface gives rise to convergence and confluence of consequent streams. The gullying action of rain on the sides of the growing consequent valleys will initiate short tributaries which cut into the interfluves by headward erosion. In the simplest case these will be oblique in direction to the main stream, following the resultant slope of valley side and general regional slope. In their turn these first tributaries will develop their own branching system of affluents, and so on, till, in the ideal theoretical limit, the whole surface will be resolved into slopes leading down to drainage channels. In areas of homogeneous rocks such a process gives rise to a simple, tree-like or *dendritic*, drainage plan (Fig. 105). The texture of the drainage net will obviously depend, *inter alia*, on the amount of rainfall and the proportion of run-off, *i.e.* the perviousness of the rocks. W. S. Glock has sought to trace a systematic cycle of development in such a drainage system (Fig. 105). During the earlier stages a process of *extension* prevails, involving lengthening of the streams by headward erosion and multiplication of tributaries. Later *integration* begins, whereby the drainage system is simplified. This involves the absorption of minor by major valleys (p. 192). The scheme has value as a mental standard of comparison, but its full development presupposes simple and uniform conditions both of structure and of climate. In the comparative study of the texture of actual drainage systems, the complications introduced by variations of rock character and differences of rainfall must be fully recognized.

Of great general importance in the growth of drainage systems is the development of *subsequent* tributaries. Such streams, starting as gullies on the sides of the primary consequent valleys, discover and explore belts of structural weakness, due to softer strata (Fig. 84), fault- or joint-planes, and shatter zones. In virtue of their chance-found advantage, subsequent tributaries establish a long start in both headward and downward erosion and pick out the natural structural lineaments, or master lines,



[*After Glock.*

FIG. 105.—IDEAL STAGES IN THE DEVELOPMENT OF A DENDRITIC DRAINAGE SYSTEM.

1, Initiation. 2, Elongation. 3, Elaboration. 4, Maximum extension. 5 and 6, Stages in integration.

of the landscape. This marks the beginning of "adjustment to structure."

In many familiar cases the nature of the structural control of subsequent streams is evident, but this is not necessarily the case. Headward erosion, in probing the rocks, may react to differences of resistance which escape the notice of the geologist. It should be noted that all the first generation of tributaries to consequent streams are "subsequent," in the sense that they arise subsequently to the establishment and incision of the consequent streams. By usage, the term "subsequent" has a narrower connotation, referring to cases of obvious

structural guidance. Tributaries of which the position and direction appear to have been determined "by chance," *i.e.* by slight and unknown causes, may be called *insequent*. The term is evidently applicable to most of the tributaries of a dendritic drainage system.

The distinction thus drawn between subsequent and insequent tributaries may well appear unsatisfactory to the reader, and it certainly has more practical than theoretical validity. The real distinction lies in the presence or absence of *regularity* in the drainage pattern. The structural features picked out and emphasized by subsequent streams, whether they depend upon the form of

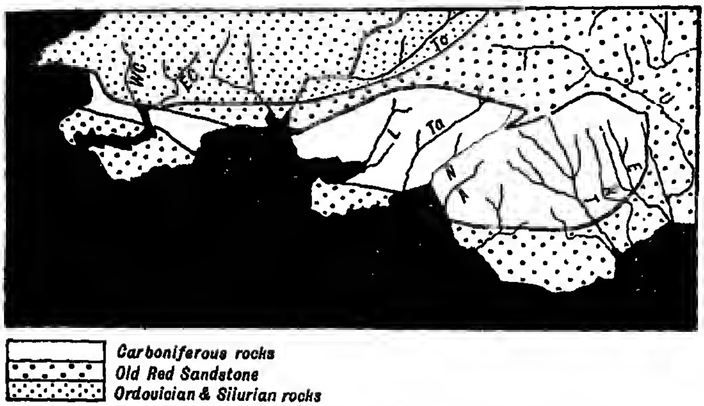


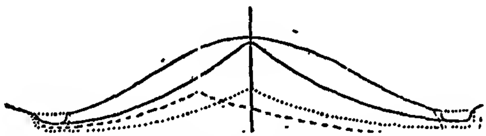
FIG. 106.—THE DRAINAGE OF SOUTH WALES.

WC, W. Cleddau; EC, E. Cleddau; To, Towy; L, Loughor; Ta Tawe; N, Neath; A, Avon; T, Taff; R, Rhymney; E, Ebbw; U, Usk. The area shown as O.R.S. along the coast includes also Carboniferous and later rocks.

rock outcrops or the pattern of fracture systems, generally (though not necessarily) show a recognizable element of regularity or repetition. This, then, becomes our working criterion in distinguishing subsequent drainage in regions of which the structure is incompletely known. In the common case of "scarpland topography," considered below, the consequent streams run *transverse* to the grain of the country, while subsequent streams have developed *longitudinal* valleys on the less resistant rock belts which trend more or less at right angles to the "consequent" direction. In the South Wales coalfield (Fig. 106), the Vale of Neath is essentially a subsequent valley developed along a line of disturbance, probably a shatter belt, oblique to the

line of the former consequent valleys directed towards the south-east, and it serves to define a subsequent direction followed by other streams in the western part of the coal-field. Similarly, the influence of master-jointing on valley plan is visible in many granite regions. In all such cases, whether the network of major valleys is rectangular or rhomboidal, the drainage plan may be described as "trellised," and one of the dominant directions will generally be found to be marked by subsequent valleys.

The migration of divides : river capture.—In the earlier stages of drainage development, the divides between streams are indistinct, but the partitioning of the area by tributaries with the approach to maturity is marked by an increasing definition of divides. A process of divide migration then ensues, owing to the fact that neighbouring streams are corrading, and therefore facilitating the wasting of their valley sides, at different rates. The principle



[After Cotton.

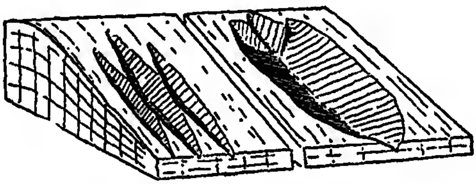
FIG. 107.—PROFILE OF A SHIFTING DIVIDE.
Lowering of divide without shifting, dotted lines ; with shifting, dashed lines.

here involved is sometimes termed the "law of unequal slopes," which was first clearly enunciated by Gilbert, in his classic study of the Henry Mountains of Utah. The steeper slope of an asymmetrical ridge or divide wastes faster than the gentler slope and the crest-line migrates away from the more actively corrading river (Fig. 107).

In regions of high rainfall, characterized also by relatively soft and impervious rocks, it is likely that divide migration proceeds actively, early in the cycle. By this means the large number of consequent streams is reduced. Those possessing some initial advantage widen their valleys at the expense of those of their neighbours, collecting them as sub-parallel tributaries, or absorbing them altogether (Fig. 108). To this process the term "stream abstraction" has been applied. For obvious reasons it can rarely be observed in operation, except under small scale or semi-artificial conditions, as on tip-banks or cliff-slopes. After this brief and early stage of "natural

selection " is over, the migration of all divides will continue with the progress of the cycle. The further migration of consequent or primary divides, is, in general, slow. Indeed, all divides separating *parallel* streams possess a certain general stability, despite limited migration, for it requires violent disproportion of activity on the two sides to re-enact the phenomenon of stream abstraction—virtually " divide destruction "—during the phase of maximum relief. In old age, under the conditions pictured by Crickmay such divides may be breached and ultimately destroyed by lateral planation (Fig. 104).

The migration of secondary divides, more particularly those separating streams of which the directions are inclined to one another at large angles, or heading in opposite directions, can lead to much more striking results, amounting, in the limit, to actual drainage diversion or river-capture. Fig. 109 illustrates stages in the capture



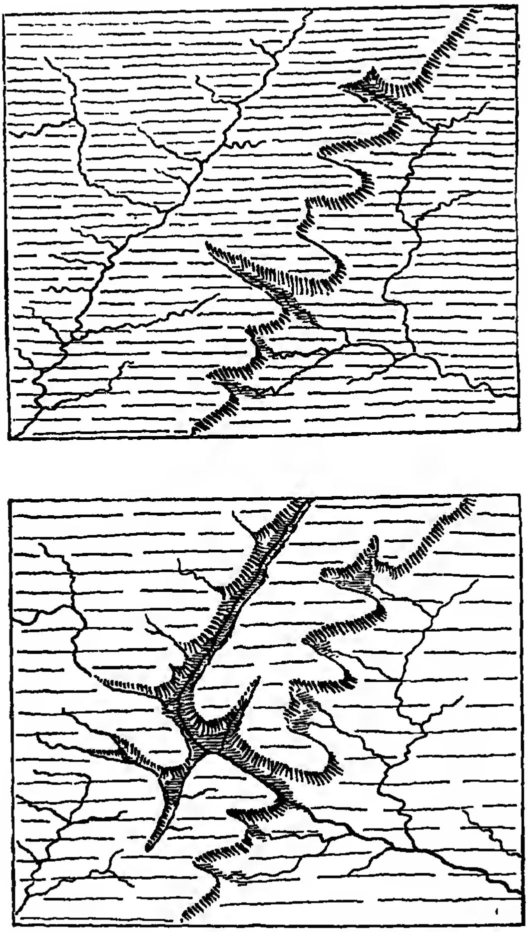
[*After Cotton.*

FIG. 108.—STREAM ABSTRACTION.

of the headwaters of the River Chattahoochee by those of the River Savannah, in the South-east United States. The full circumstances of this interesting capture, as reconstructed by D. W. Johnson, are too complex for recital here, but it will serve as a striking illustration of capture, in which one river is enabled to take the other on the flank. It should be noted that Tallulah, where the capture has taken place, is much farther from the Gulf coast via the Chattahoochee drainage than from the Atlantic coast by way of the Savannah.

Consider next the commoner case of two subsequent streams heading in the same belt of weak strata and flowing in opposite directions, each to its own consequent trunk. If one of the consequent streams is degrading its course faster than its neighbour it lowers the effective base-level for its subsequent tributary, which, excavating in soft rocks, shows a rapid response in deepening and headward corrasion. It may thus progressively encroach

on the territory of its neighbour subsequent stream (Fig. 110), continually shortening it. At length, the conditions of Fig. 111 will be reached, analogous in some respects to the case described above, and the final result

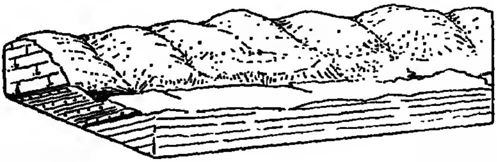


[*After Johnson, simplified.*

FIG. 109.—CAPTURE OF HEADWATERS OF R. CHATTAHOOCHEE BY R. SAVANNAH AT TALLULAH FALLS, GEORGIA.

must be the diversion of the less successful consequent by an "elbow of capture" into the basin of its vigorous neighbour. The unsuccessful consequent is thus *beheaded*, and, deprived of its headwaters, will dwindle in size and

become a *misfit* or *underfit* river, too small for the valley in which it flows. Under suitable circumstances a dry col or *wind-gap* may come to mark its former crossing of

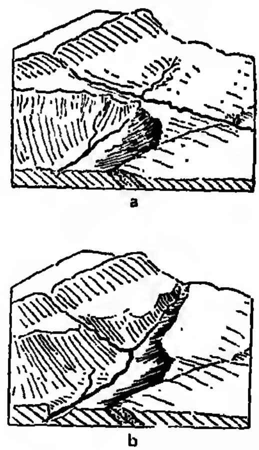


[*After* Cotton.

FIG. 110.—CONDITIONS OF IMMINENT RIVER-CAPTURE IN A SUBSEQUENT LOWLAND.

The stream on the left is encroaching at the expense of that on the right.

the resistant stratum below the point of capture. The floor of the wind-gap will be left at a higher level than that of the neighbouring water-gap, deepened by the continued vigorous action of the successful consequent stream. Fig. 112 illustrates two wind-gaps abandoned through capture in the country north of London. It will be noticed that short reversed (or *obsequent*) streams flow from the wind-gaps into the capturing subsequent stream. Further reference to this region will be made in the sequel (p. 211).



[*After* Davis.

FIG. 111.—RIVER-CAPTURE.

(*a*) Imminent. (*b*) Completed.

It is important to realize that river-capture does not occur under the above-mentioned simple conditions only. It is a normal incident in a veritable struggle for existence between rivers, and may occur in very varied circumstances—wherever, in fact, divides migrate rapidly under the influence of unequal erosion. There are few regions in Britain which do not bear the impress of river-capture, though if a long period has since elapsed, detailed evidence of the occurrence may be wanting (p. 211).

The causes of the inequalities which set in train the changes leading to river-capture may be either climatic or geological. For whatever reason the trunk stream is accelerated, or retarded, in its work,

the effects are felt to the extreme limits of its drainage basin, and it is for this reason that such marked contrasts in erosive power may be manifest near the mutual boundary of two drainage basins. Moreover, since renewed downward corrasion is very often initiated at and propagated back from the coast, distance from the sea, measured along the

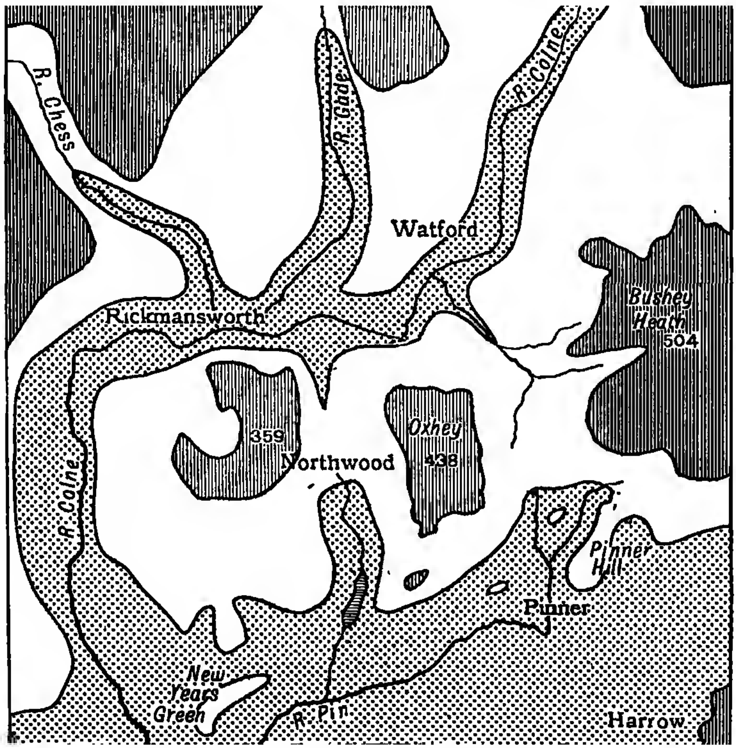


FIG. 112.—WIND-GAPS NEAR WATFORD.

Ground below 200 feet dotted, above 300 feet shaded. 1 inch = 1·5 miles (approx.). A subsequent reach of the R. Colne has captured the headwaters of the R. Gade and the Upper Colne.

river courses, often gives the measure of a stream's "aggressive" possibilities.

Examples of adaptation to structure.—A survey of the existing land areas reveals a great variety of structural types and assemblages, and in a full morphological survey each case would need separate examination to make clear the interaction of structure and sculpture. We must here confine our attention to two cases of

systematic importance and widespread occurrence, viz. (*a*) regions of uniclinal structure, (*b*) regions of close-spaced parallel folding.

The evolution of topography in regions of uniclinal structure.—Regions of uniclinal structure are those in which a general regional tilt has been given to the constituent rocks. If a thick succession of stratified rocks of varying resistance is thus disposed, the resulting landscape is of the "scarpland type." Traced over a wider area, such regional tilting will often appear simply as an integral part of gentle or open folding, *i.e.* the uniclinal tracts mark the flanks of broad basins, or arches. The

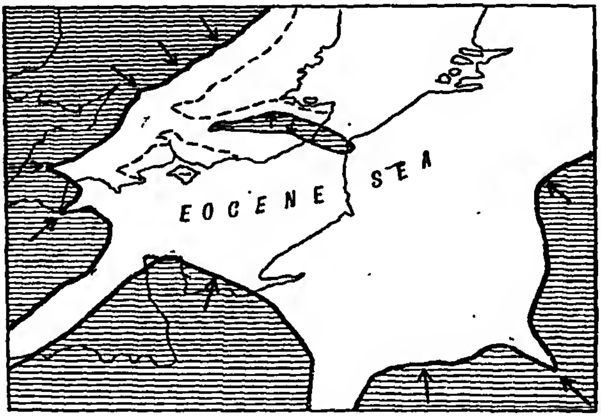


FIG. 113.—THE ANGLO-GALLIC BASIN OF EARLY TERTIARY (EOCENE) TIMES.

Directions of drainage indicated by arrows.

movements responsible for such a structure have generally begun during the accumulation of the later rocks of the series. They are brought to completion with the final uplift above sea-level of these youngest sediments.

We may select the Anglo-Gallic basin of Early Tertiary times as an example of such a region. The extent of the Early Tertiary (Eocene) sea is indicated in Fig. 113. The older rocks (Chalk, etc.) of the surrounding land area were already inclined towards the margin of this down-warped region. Rivers bore sediment to the basin from the south, west, and north-west. Near the centre of the basin, an elongated island marked the site of the present Wealden region, and its flanks must have been drained by small streams. At a later date uplift converted all or most of

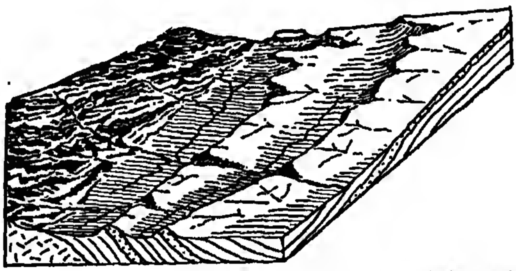
the region shown into land. At the time of the uplift, the marginal tilt around the basin was increased, and the Wealden uplift was further emphasized. The earliest drainage over the uplifted Tertiary sea-bottom must thus have repeated and extended the centripetal pattern of the earlier drainage, from the surrounding land, subject to the major complication introduced by the Wealden uplift. The emergent surface consisted of constructional slopes defining constructional basins, and the consequent drainage arose in harmony with these conditions. Since then, various major derangements of the simple scheme have taken place, notably the submergence of the English Channel region. Nevertheless, the existing plan of the drainage, both in England and France, shows a plain relationship to the ancestral conditions of Tertiary times. The north-western margin of the basin, to-day the region of the English Plain, affords a good example of a region of fairly simple uniclinal structure, and exactly similar conditions exist in North-east France. In both regions, the thick stratum of Chalk which immediately underlies the Eocene rocks has been cut through and worn back, revealing the underlying Jurassic and Triassic sediments. Elsewhere, as on the western and north-eastern sides of the Paris Basin, the progress of erosion has uncovered older, more resistant rocks, forming the North-western Massif of France and the Ardennes Massif. The drainage conditions are thus more complicated.

Uniclinal structure also arises under the conditions exemplified by the Atlantic Coastal Plain of the United States. This region consists of marine and other rocks recently uplifted with an easterly tilt, and added to the margin of the older Appalachian land area (Fig. 147). Such an episode must typify a common method of " continental growth." The axis of uplift or tilting was parallel with the old Appalachian ranges and the existing coastline ; hence the grain, or strike, of the structures maintains a simple linear course for hundreds of miles. New consequent streams arose on the uplifted sea-floor, and older streams " extended " from the Appalachian land-mass to the new coastline.

It should be noted that the coastal plain conditions which are simply exemplified in the Eastern United States, in relation to an existing coastline, may be regarded as holding for the margins of the Anglo-Gallic Basin, in relation to the Eocene coastline. Thus the South-east

Midlands of England lie between the former Eocene coastline and the old massifs of Wales, etc. (representing the Appalachians), and the French scarplands are similarly interposed between the Eocene coastline and the uplands of the Central Massif and the Vosges.

Assuming the conditions of a simply constituted coastal plain adjoining an " old land " (Fig. 114), let us trace the first establishment of subsequent streams. The consequent streams incise themselves in the constructional slope formed, we will suppose, by a relatively strong stratum, *e.g.* limestone. With the progress of down-cutting they will reveal the underlying softer sand (Fig. 115) in " valley inliers." At these points the profile



[*After Davis.*

FIG. 114.—COASTAL PLAIN OF SEDIMENTS RESTING UNCONFORMABLY ON OLDER ROCKS, WHICH EMERGE LANDWARD TO FORM AN " OLDLAND."

of the valley will become more open, and valley-side gullies will extend readily in the soft sand, eating back into and undermining the limestone cap. Thus subsequent streams will be initiated, and with the deepening and widening of their valleys the edge of the main limestone mass will appear as an escarpment, while limestone outliers might survive for a time on the slopes of the " old land." The expansion of the subsequent valleys of neighbouring consequent basins will develop a " strike-vale," along the sand outcrop at the foot of the escarpment.[1] Streams will descend the scarp-face to join the subsequent rivers. These are classed as *obsequent* streams, or *anti-dip* streams. Where, under similar conditions, several such escarpments develop, the subsequent rivers will also receive tributaries flowing down the dip-slopes of escarpments ;

[1] It is this phenomenon which gives rise to the " peripheral lowland " around the northern margin of the Massif Central of France. Peripheral lowlands, in this sense, are the innermost strike-vales developed in a series of gently inclined sedimentary rocks dipping away from the margin of a massif or " old land."

these are parallel with the original consequent streams, and have been called *sub-consequent or secondary consequent streams.* These terms are, however, in some respects misleading, and are better replaced by the simple designation " dip-stream."

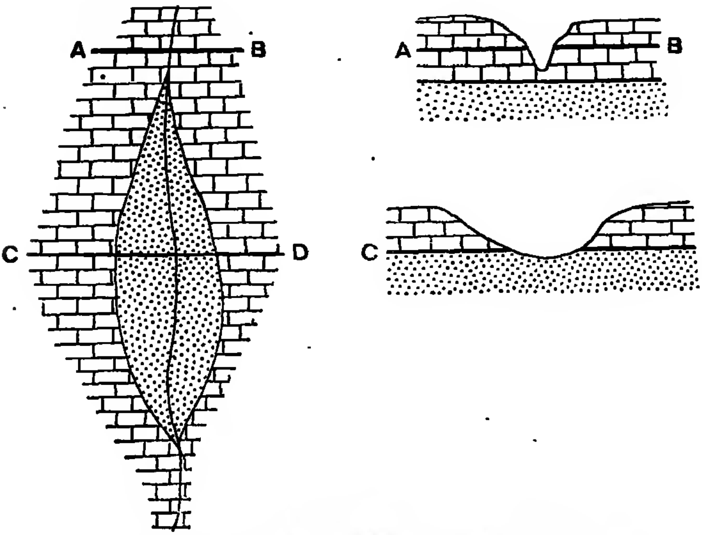


Fig. 115.—Valley-inlier in Consequent Valley.
At such points subsequent tributaries are likely to be initiated.

The coastal plain, when maturely dissected, thus takes on the form of a series of strike-vales, separated by asymmetrical uplands, or *cuestas,* each showing a scarp-slope and a dip-slope. The drainage pattern in the simplest case is notably rectangular, consisting of parallel

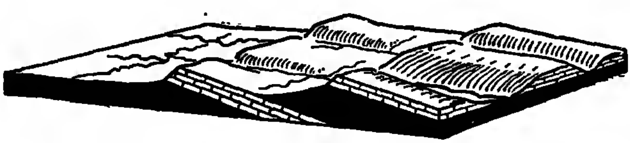
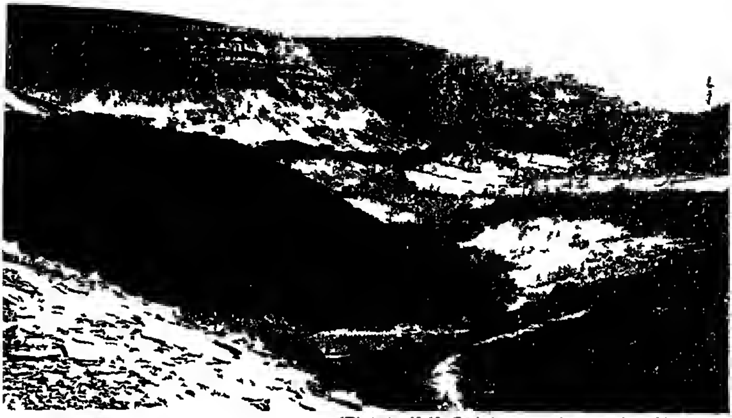


Fig. 116.—A Scarfland with Trellised Drainage.

consequent streams, subsequent tributaries more or less symmetrically developed, and again, dip and anti-dip (obsequent) streams tributary to the latter. We have already noted how such an arrangement facilitates river-capture, and in normal circumstances this will follow inevitably with the progress of the cycle (Fig. 116).



[Photo by H M Geol Survey Crown copyright reserved

FIG 117 —EGLWYSEG MOUNTAIN, THE ESCARPMENT OF THE CARBONIFEROUS LIMESTONE, NEAR LLANGOLLEN, DENBIGHSHIRE

The lower ground is formed of Silurian mudstones on which the limestone rests unconformably

[Photo by A J Dale

FIG 118 —THE ESCARPMENT OF THE SOUTH DOWNS, LOOKING EASTWARDS FROM BURY HILL, SUSSEX

The character of scarpland landscapes reflects in large measure the thickness and spacing of the scarp-forming elements. The form of the escarpments depends on the dip of the stratum concerned, the height being inversely proportional to the dip. In the limiting case of horizontal strata, the scarp-face is equal in height to the thickness of the stratum and the dissection of such a rock sheet gives rise to tabular masses, to which the name "mesa" has been applied. With a high dip the inclination of the dip-slope may become equal to, or greater than, that of the scarp-slope, and in this way more or less symmetrical "hog-backs" arise. A good example of the influence of dip on escarpment form is afforded by the range of the North Downs in Kent and Surrey. South of

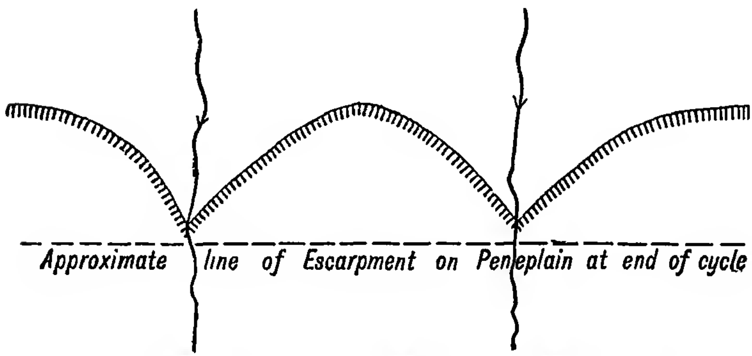


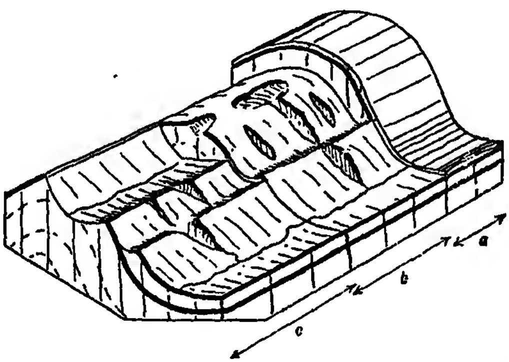
FIG 119.—RE-ENTRANTS AND SALIENTS IN MATURE ESCARPMENT.

London, where the dip is low, the escarpment is high and the dip-slope is broad and plateau-like. The dip increases westwards, as is shown by the narrowing of the Chalk outcrop, and near Guildford the increase is so rapid that the escarpment rapidly loses height. Beyond Guildford, where the dip reaches 30°, the escarpment is represented by the well-known "Hogs Back," a roughly symmetrical ridge less than a mile wide.

Escarpments undergo systematic changes of form during the passage of a cycle. In maturity their initial straightness becomes broken. Transverse valleys are marked by re-entrants, while salients mark the interstream areas (Fig. 119). The escarpment, as a whole, shows the phenomenon of "uniclinal shifting," receding in the direction of dip in accordance with the "law of unequal slopes," and losing elevation in the process. When active down-

cutting has ceased in the transverse valleys no further recession of the edge of the scarp-forming stratum is possible here; but during the later stages of the cycle, recession can continue in the salient areas, and will ultimately obliterate the salients. On the final peneplain, the straightness of the original outcrops will be re-established, though the escarpments themselves will have disappeared, save for an occasional low monadnock. The peneplain will consist of alternating belts of hard and soft rock, covered to a large extent by river alluvia and rock-waste. Such a surface is termed a " belted outcrop plain."

The evolution of topography on folded rocks.—A somewhat different set of land-forms will develop from an initial surface which, with the rocks beneath it, has been



[*After Cotton.*

FIG. 120.—DEVELOPMENT OF SUBSEQUENT DRAINAGE ON FOLDED ROCKS. The blocks *a*, *b*, and *c* represent three stages of dissection.

thrown into parallel folds, fairly closely spaced. The main consequent streams will here flow along the synclines, forming *longitudinal consequents*, the direction of flow being determined by the *pitch* of the folds. These streams will have *transverse consequent* tributaries flowing down the slopes of the structural arches (Fig. 120), and therefore commonly favoured with a steep initial gradient. The rapid down-cutting performed by these streams will enable them, in suitable circumstances, to develop subsequent tributaries which will be parallel with the original longitudinal consequent streams (Fig. 120). The rapid growth of these subsequents will breach the crest of the arches, which will become strike-vales bounded by inward-facing escarpments. Thereafter, the subsequent streams,

cutting in soft rock, will deepen their valleys faster than the original longitudinal consequent streams, leading to rapid recession of the escarpments and to progressive diminution of the drainage area lying within the synclines. In the limiting case, the longitudinal consequent systems may be eliminated entirely, the synclinal areas remaining as ridges capped with a remnant of the escarpment-forming stratum (Fig. 121). This clearly involves an "inversion" of the original relief. The general synclinal structure of ridges, and masses of high ground generally, is a common phenomenon. It is often explained by supposing that anticlinal arches, subjected as they are to stretching or tension, are structurally unstable, and particularly amenable to the attack of weathering agents acting along tension joints and rifts. While this is in a measure true, inversion of relief is more truly attributed in most cases to the successful competition of subsequent with consequent streams, as outlined above. It also implies that the surface in question is far below the initial surface, and that a correspondingly long period has elapsed since the initiation of erosion.

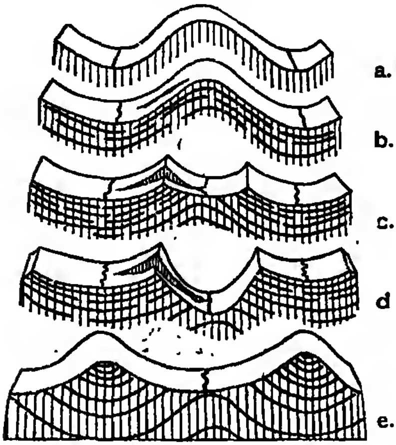


FIG. 121.—STAGES IN THE DEVELOPMENT OF INVERTED RELIEF (SYNCLINAL RIDGES).

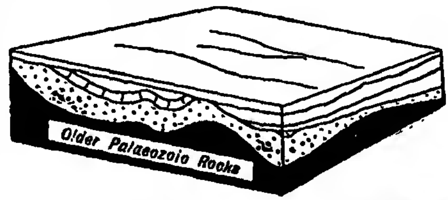
Uninverted relief is not common, but some outstanding examples may be cited. In the Jura Mountains, the longitudinal valleys are synclinal (see further, pp. 212, 213), though the stripping of the anticlinal arches has made considerable progress in some areas. In South-west Ireland, anticlinal ridges of Old Red Sandstone separate synclinal vales, sited on softer Carboniferous rocks. Similarly, in the Chalk tracts of Hampshire, the east-west valleys are predominantly synclinal. Although in these cases the relief is uninverted, there is good evidence that we are not dealing with an initial surface, and the longitudinal streams are not necessarily to be regarded as

consequent. The origin of such synclinal valleys is more complicated, and is dealt with in a later section (p. 213).

Inconsequent drainage.—In the cases considered above, there is a systematic relation between the drainage plan and the structure, observable not only in the subsequent adjustments but also in the direction of the consequent streams. Where such relations are absent, the drainage may be termed "inconsequent." Inconsequent drainage may arise in at least two ways, which must now be considered.

Superimposed Drainage

Where a sedimentary covering, whether marine or continental in origin, rests on an older land-surface, any drainage system freshly initiated upon it will conform to the disposition of the surface of the covering. In time, however, the streams will cut into the underlying basement of older rocks, but by the time this surface is reached they are firmly established in their courses and can maintain them independently of the structural features of the underlying mass. At length, the whole of the younger sedimentary cover may be removed, while the valleys have become deeply sunk in the basement rocks. Such a drainage system is called *superimposed* or *epigenetic*, and excellent examples are not far to seek. In most of the tracts of older rocks in Britain the drainage has certainly been superimposed from a cover of younger strata, since removed. It is agreed that the rivers of South Wales were initiated on such a cover, of which the surface was tilted towards the south and east (Fig. 122). To-day we find the main streams making their way across the great coalfield syncline, flowing first with the dip of the rocks and then against it (Fig. 106). The Lake District provides a further instance of superimposed drainage. The mountainous heart of this district constitutes an inlier of older Palæozoic (Ordovician and Silurian) rocks, highly folded and faulted. On all sides these rocks disappear



[*After Trueman*

FIG. 122.—INITIATION OF THE SOUTH WALES DRAINAGE ON A COVER OF MESOZOIC ROCKS.

Between the Mesozoic and the older Palæozoic rocks (black), the Old Red Sandstone and the Carboniferous rocks are shown.

beneath a cover of newer strata, of which the oldest member is the Carboniferous Limestone (Fig. 123). The older rocks are anticlinally disposed about an axis passing east-north-east–west-south-west through the north of the inlier, near Skiddaw. The valleys, however, radiate from a water-shed considerably farther south, passing roughly east to west near Scawfell and Helvellyn. This water-shed marks the crest of a broad anticlinal uplift in which

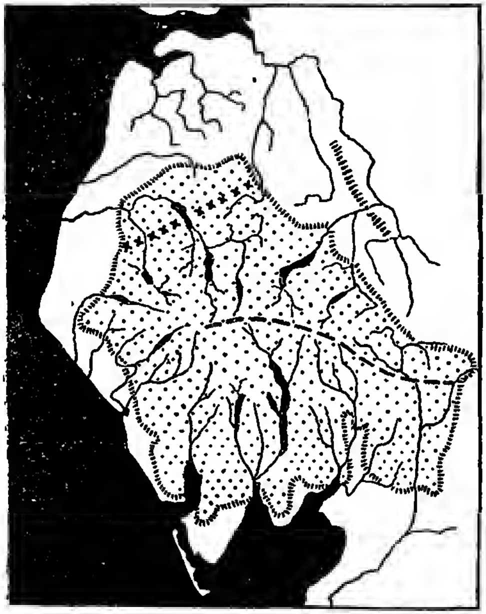


FIG. 123.—DRAINAGE OF THE LAKE DISTRICT.

Older rocks dotted and surrounded by Carboniferous Limestone escarpment. Escarpment of Penrith Sandstone also shown. (Cf. Fig. 53.)

the cover rocks were involved. With the removal of the cover, the drainage system on the older rocks has retained in large measure its radial plan. It is probable that the uplift responsible for the drainage was Tertiary in date, and involved a covering of Chalk, since removed from the whole area. The Chalk would have rested discordantly on all the older rocks (pp. 248, 252); so that the superimposition has been double, first from a cover of Chalk on to older Mesozoic and Carboniferous rocks, and then from the latter on to the older Palæozoic rocks.

A superimposed drainage system may be adjusted to structure to a considerable extent, both during removal of the cover and after arrival on the basement surface. Fig. 123 indicates considerable development of subsequent streams on the eastern side of the Lake District area, along the present edge of the cover; *i.e.* at the foot of the Carboniferous Limestone escarpment. Similar adjustment has taken place at the foot of the escarpment of the Penrith Sandstone (Permian). In both cases it is possible to trace the line of former consequent streams, now beheaded by capture. Considerable adjustment to structure is also in evidence within the Lake District proper, where subsequent streams have developed along the softer slate bands and shatter zones among the older rocks. Similarly, in South Wales, the Tawe, Neath and Avon valleys may be regarded as subsequent developments structurally guided, which have broken the continuity of former consequent streams directed towards the south-east (Fig. 106). It is clear, therefore, that lack of adjustment to structure cannot be made the criterion of superimposition. We are concerned, rather, with the absence of relation between presumed consequent streams and the structure of the rocks over which they flow.

The great continental formations, such as the Old Red Sandstone and the Permo-Trias, rest, in places, on irregular land-surfaces. The hills and valleys of the latter have been completely buried under the later rock-mantle, but if drainage is superimposed on such a surface it may exhume the ancient landscape in part. Such conditions are almost exactly realized in Charnwood Forest, where an irregular landscape of resistant Pre-Cambrian rocks is in course of reappearance following the removal of a cover of soft Triassic marls. On the other hand, drainage superimposed under these conditions may successfully ignore the form as well as the structure of the undermass. In the Bristol district, the removal of the Triassic marl cover has brought to light a number of Pre-Triassic ridges formed of Palæozoic rocks (Fig. 124). The streams of the district trench these hills in striking gorges, of which the chief is the famous Clifton Gorge of the Avon, below Bristol. The general lowering of the country has brought into being possible low-level routes round these obstacles, but the drainage was established in its courses long before such routes became available.

Antecedent Drainage

A second type of inconsequent drainage arises where a river is able to degrade its course sufficiently fast to keep pace with an uplift rising across its path. Such rivers are termed *antecedent.* It is considered that the Columbia River has thus maintained its course across the rising Cascade Range, while the Ogden River, draining to the Great Salt Lake, is regarded as antecedent in respect of the recent uplift of the Wasatch Range. Similar claims have been made for the head-streams of the Indus and Brahmaputra crossing the Himalayan ranges. In

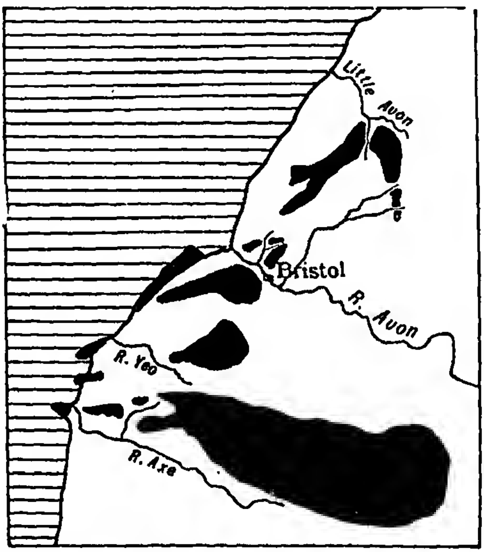


FIG. 124.—PALÆOZOIC RIDGES OF THE BRISTOL DISTRICT, WITH SUPERIMPOSED DRAINAGE.

Britain the course of the Lune between Tebay and Low Gill has been treated by some as antecedent to the uplift of the Lake District–Howgill Fells watershed (Fig. 123). However, this gorge, which forms such a vital link in the railway communications of North England, may be explained by headward extension of the Lune across the watershed, with resulting capture of streams beyond. Kindred explanations should always be considered in dealing with cases of apparent antecedent drainage.

In New Zealand, certain rivers, such as the Waipara, Hurunui, and Waiau of North Canterbury drain eastwards

to the sea through gorges in uplifted blocks. It is certain that these streams are antecedent to the greater part of the uplift, but their courses may have been established as the result of earlier movements of the same series. For such streams Cotton has proposed the term "ante-consequent," since they are "consequent on the earlier, and antecedent to the later stages of a single series of deforming movements."

It will be clear that the demonstration of antecedent or ante-consequent relations demands accurate knowledge of the uplift history of an area, often difficult or impossible to obtain. The hypothesis of antecedent drainage, therefore, requires careful and sparing use. It may more readily be invoked in the circum-Pacific lands, where recent rapid movement has definitely been in progress, than in the more stable areas of Eastern North America, Western Europe, etc.

The term "antecedent drainage" should *not* be applied to cases in which there has been general uplift of the whole area, with resulting incision of all streams (*e.g.* in the Weald). It is true that the streams in the Weald may have flowed over a peneplain prior to the uplift, and having thus a long prior history they are, in a general sense, antecedent to all the existing land-forms. If, however, the technical term "antecedent" were thus extended, it would embrace nearly all drainage systems. The essence of the antecedent relationship is a successful contest waged by rivers against *localized* uplift.

CHAPTER XV

DENUDATION CHRONOLOGY

The revival of relief.—No actual or average duration in years can be assigned for the completion of a cycle of erosion; it must clearly vary widely with conditions. Nevertheless, it is certain that the periods of emergence of the land-masses often greatly exceed the length of the cycle, so that several cycles may follow one another to completion in the same area. Thus, Tertiary time represents about 60 million years, according to calculations based on radio-active minerals. During this period, South-eastern England underwent complete peneplanation at least once, while the current cycle has reached the general condition of maturity.[1] We can reach the same conclusion by another line of approach. Many regions give the plainest testimony of having passed through one or more former cycles of erosion, since they retain considerable relics of uplifted and dissected erosion surfaces. These marked the culmination of former cycles; by uplift they became the initial surfaces for current cycles, and while they remain recognizable elements in the landscape the two-cycle or multi-cycle character of the latter is readily apparent. The landscape as a whole has been *revived* by change of base-level, but bears traces of a former condition.

Second cycle of erosion in regions of uniclinal structure. Let us examine the progress of a second cycle of erosion in a region of uniclinal structure, which has been reduced to a "belted outcrop plain" and then re-elevated in respect of base-level. A trellised drainage system, in an advanced state of adjustment to structure, is already in existence and the dissection of the area by the re-excavation of strike vales will hence proceed very rapidly. In the earlier stages of the second cycle the former peneplain is revealed in the bevelled summits of the escarpments (Fig. 125). Recession must obliterate the bevel eventually; but, even then, the old peneplain will be suggested

[1] The period also embraces two marine transgressions (Eocene and Pliocene), but neither was of sufficient extent or duration to make the period, as a whole, other than one of emergence.

by the generally accordant summit levels. Further, the escarpments will, for a time, inherit the straightness of course which characterized them during the later stages of the preceding cycle (cf. Fig. 119).

It is important to note that the drainage begins its revived life in an *adjusted* state. A high degree of adjustment, combined with relatively youthful land-forms, thus becomes a criterion of the second cycle condition. The river-captures of the first cycle will still be legible in the pattern of the drainage, but there will now be no direct evidence of the former continuity of consequent drainage lines, *i.e.* the wind-gaps, opposite the elbows of capture, will have disappeared in the levelling of the earlier escarpments; their former position is high above the present land-surface. Adjustment to structure may, of course, continue and become more complete during the second cycle; further river-captures may take place, and these

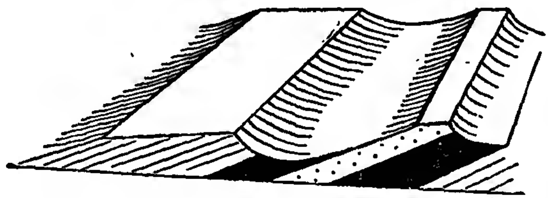


FIG. 125.—BEVELLED ESCARPMENTS

will evidently be marked by wind-gaps. An example of the juxtaposition of first and second cycle capture is afforded by the region north of London. We have noted the evidence for capture in the current cycle, near Watford (p. 195), but farther eastwards the consequent Upper Lea is diverted eastwards at the foot of the Tertiary escarpment (Fig. 126). Its beheaded continuation is recognizable, but no wind-gap marks the former crossing of the escarpment. The capture took place in a former cycle.

Second cycle of erosion in regions of folded rocks.—A second cycle of erosion will also lead to interesting results in a region of folded rocks. During a first cycle, as already noted, the tendency is for subsequent streams to grow in anticlinal vales at the expense of the longitudinal consequent streams, with the development of intervening ridges of synclinal structure. After planation and renewed uplift the subsequent streams may incise themselves in their anticlinal positions and thus lead to a topography closely resembling that of the first cycle. This will

happen if deepening proceeds in some thick, but relatively soft, stratum which forms the cores of the anticlines below the surface of the old peneplain. If, however, there is a hard bed in the folded series, unexposed in the peneplain surface but at no great depth below it, the down-cutting subsequent streams may move by uniclinal shifting down the flanks of the anticlines, destroying the synclinal ridges and ultimately tending to occupy synclinal positions closely analogous to those of the original longitudinal consequent streams (Fig. 127). Such streams are called

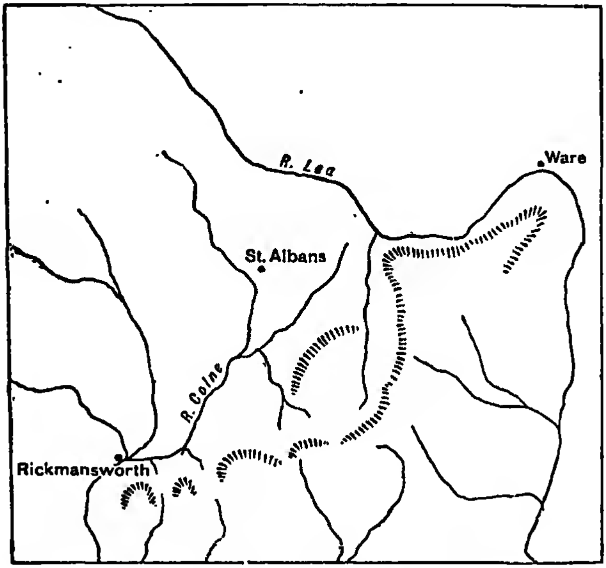


FIG. 126.—FIRST AND SECOND CYCLE RIVER-CAPTURES, NORTH OF LONDON (cf. FIG. 112).

resequent streams, and though the surface over which they flow resembles the initial surface of the first cycle it is, in fact, many hundreds of feet below it. The recognition of resequent drainage is often difficult. In some cases it depends on proof of a previous planation of the area, which definitely precludes the identification of the surface with the initial folded surface. In other cases, it may follow from a knowledge of the geological history of the area, and, more particularly, of the date of the folding. A good example is afforded by the Central Weald of Kent and Sussex, where there are many good examples of synclinal valleys for which resequent origin must be

deemed probable. The folding took place in Tertiary times and must have involved the Chalk, but the present surface is not less than 2,000 feet below the former Chalk surface which extended across the Wealden area (p. 240).

Though planation may be regarded as having commonly preceded the development of a resequent drainage, the same condition might arise during the progress of the first cycle if a suitably disposed resistant bed were encountered during down-cutting. In such case the subsequent streams might finish in synclinal positions on the peneplain, and the new cycle would lead simply to the removal of any soft infillings of the synclines. The longitudinal rivers of Northern Hampshire and the Central Weald are certainly resequent, but at what stage in the history of their regions they assumed this condition cannot be stated with certainty.

a. b. c. d.

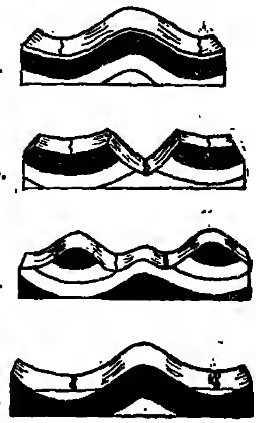


FIG. 127.—STAGES IN THE DEVELOPMENT OF RESEQUENT DRAINAGE.

The character and origin of summit-planes.—In the foregoing paragraphs we have assumed conditions in which relief is revived on the surface of a true sub-aerial peneplain which, for a time, survives as a recognizable summit-plane in the region. The landscapes of the world present us with many examples of well-developed summit-planes, but we cannot assume without further inquiry that they are all peneplains in the narrow sense of the term. Accordance of summit-level or bevelling of hill-tops of itself does not prove a former peneplain. It may, for instance, serve to mark an actual initial surface—an uplifted sea-bed. In such a case, however, the surface lies entirely in one stratum, whereas a peneplain will truncate the structures, passing indifferently across various strata. The same discordance to structure will, however, characterize a simple plain of marine denudation or a plane of unconformity, however fashioned, exhumed from beneath a sheet of "cover-rocks" (Fig. 128). All these possibilities must be envisaged in investigating regional summit-planes.

It must be admitted that but few infallible criteria exist for the distinction of sub-aerial from marine erosion

surfaces, as such. The search for relics of marine deposits is often fruitless, and, even if successful, it leaves us in doubt as to whether such relics represent the thin partial cover of a true plain of marine denudation, or the basal members of a thin sedimentary succession, stripped from a plane of unconformity. It might be expected that residuals, *i.e.* islands projecting from a marine plain, would show steeper slopes, due to cliffing, than sub-aerial monadnocks, but this is a distinction which would tend to pass with the passage of time. The most likely means of differentiation lies in the fact that a drainage system, initiated *de novo* on the plain of marine denudation, has all its way to make in the matter of adjustment to structure,

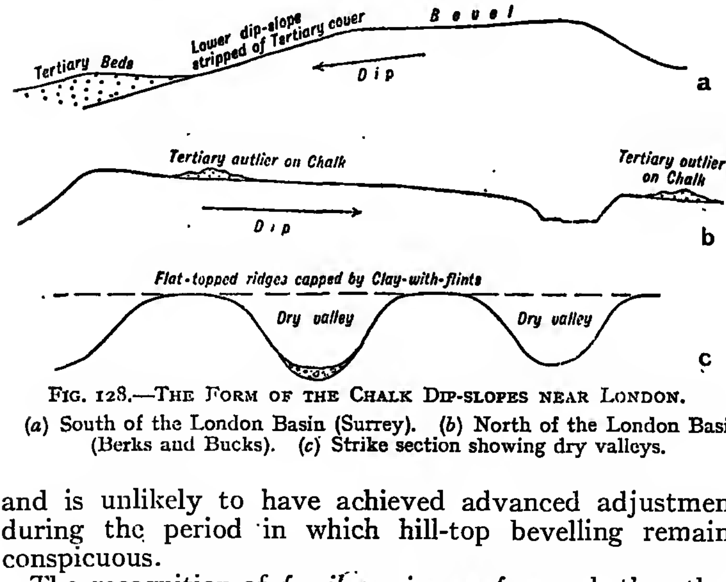


FIG. 128.—THE FORM OF THE CHALK DIP-SLOPES NEAR LONDON.
(*a*) South of the London Basin (Surrey). (*b*) North of the London Basin (Berks and Bucks). (*c*) Strike section showing dry valleys.

and is unlikely to have achieved advanced adjustment during the period in which hill-top bevelling remains conspicuous.

The recognition of *fossil erosion surfaces*, whether they be marine or sub-aerial in origin, presents other problems. In general, we shall not strongly suspect such an origin for a regional summit-plane unless it is cut in older rocks and can be linked in imagination with a plane of unconformity, demonstrable beneath younger rocks within the same major region (Fig. 129). In fortunate cases we may find outliers of the cover surviving on parts of the surface, but, if such are absent, we must base our conclusions on the general geological history of the area and the attitude of the surface in question. It will often be found

that the basal planes of cover rocks, projected towards upstanding uplands of older strata, pass far above their surfaces. We must remember, however, that the gradient of such basal planes is not necessarily uniform, and may have decreased as traced away from the downwarped lowland tracts towards bordering plateaux. It is even possible to conceive of monoclinal bending of such surfaces near the margin of the plateau area. However, if the upland surface and the basal surface of the cover can be traced close to one another, and shown to intersect in a distinct angle (Fig. 129), there will be a strong presumption that the upland surface is the younger of the two, representing a primary, not a fossil, feature. The degree of adjustment of the drainage also bears on the matter, for, as we have seen in the previous chapter, superimposition of the

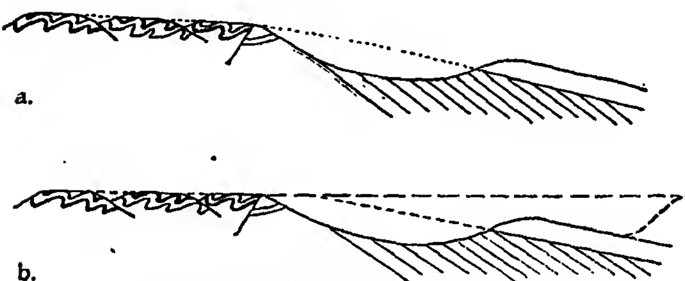


FIG. 129.—THE DATING OF A SUMMIT-PLANE.
(*a*) By projection of a plane of unconformity. (*b*) By projection of another hill-top surface.

drainage must defer adjustment even longer than in the case of a simple plain of marine denudation.

Whether a regional summit-plane be a primary or a secondary surface we must be prepared to seek evidence of warping during uplift, shown by the differing altitudes of unconsumed parts of the surface. Such warping may modify the drainage system inherited from the previous cycle, deranging the balance between neighbouring systems and setting in train new adjustments to structure.

The concept of successive cycles of erosion.—The concept of successive cycles of erosion has powerfully affected the views held by geologists on the sculpture of certain mountainous regions. In older writings the mountains of Wales and Scotland were regarded as having arisen by long continuous denudation acting upon the very ancient rock-folds of these areas. It is now universally recognized

that in these, and many similar cases, complete planation occurred once, and probably more than once, so that the topography bears no relation to that of the original folded surface. In Wales, the existence of a widespread summit-plane at 1,500 to 2,000 feet O.D. is readily recognized in the view from the higher summits. These latter, Cader Idris, Plynlimon, etc., rise as monadnocks above the ancient plain, but most of the mountains have come into being during its dissection (cf. Chapter XIII). In the Highlands of Scotland a general summit-plane, at an elevation of about 2,000 feet, is readily recognized in the view from the higher peaks of the Grampians.

We are thus led to recognize that structural features are, in general, old in comparison with the age of the relief-forms. The only regions available for study which are in their first cycle of erosion are narrow strips of coastal plain, but recently uplifted from the sea, and young volcanic mountains or lava-plains. In most other cases reconstruction of the physiographic history leads us back to some uplifted erosion-surface, not always indeed a peneplain, but a surface which implies previous erosion and former land-forms, now perhaps completely vanished. It is important to realize that the earlier cycles of erosion in an area have often left no trace of themselves; their existence is inferred on general grounds only. Thus, in many areas, the outcrop plain is the only initial surface which need be considered in dealing with existent land-forms. In elementary treatments of the subject of river-development it is commonly assumed as a starting point, but this must not blind us to the fact that the only real initial surface in a normally constituted land-area is an uplifted sea-bed. In areas of newer rocks, such, for instance, as South-east England, it is possible to recognize the date of the last general emergence, and thus to gain some idea of the total amount of denudation which has taken place, and to form a rough estimate, at least, of the number of complete cycles which may have been involved in land-form development. Terrains of older rocks are very much more difficult to deal with. The earlier stages of their denudation must generally remain a closed book, and we must content ourselves with recognition of the initial surface, generally a peneplain, of the current cycle of erosion. But while the details of earlier cycles are often perforce unknown, their existence is not in doubt. The surfaces of the lands, no less than the sediments of the

[*Photo by H.M. Geol. Survey. Crown copyright reserved.*

FIG. 130.—THE LONGMYND FROM CAER CARADOC.

The Church Stretton valley in the foreground bounded by a fault-line scarp on its further (western) side. Even summit-plane of the Longmynd bevelled across steeply inclined Pre-Cambrian rocks.

[*Photo by H.M. Geol. Survey. Crown copyright reserved*

FIG. 131.—INCISED MEANDERS IN THE RHEIDOL VALLEY, PONT ERWYD, CARDIGAN.

Note the upper valley with broad flat floor below which the meanders are incised.

sea-floors, enforce the truth of Hutton's classic dictum "No trace of a beginning, no prospect of an end."

Rejuvenation of relief—If the cycle of erosion is relatively short compared with the intervals separating major earth-movements, it is, nevertheless, long in relation to the periods of minor changes of base-level. The cycle can only move uninterruptedly to its close if it coincides with a period of *still-stand, i.e.* of unvarying base-level, unaffected by major climatic change. It is also sensitive to such local and sporadic occurrences as volcanic eruption.

On general grounds it is very improbable that a cycle of erosion has ever followed a completely unchequered course. Of greater practical importance is the fact that current cycles of erosion, which alone are available for our detailed scrutiny, reveal the plainest evidence of frequent small changes of base-level, and, locally, of other sources of interference. It is usual to class slight changes of base-level as *interruptions* of the cycle, while climatic or volcanic changes are classed as *accidents*. The latter are, on the whole, of small systematic importance, and will not concern us here.

The strictly logical treatment followed by W. M. Davis treats any change of base-level as initiating a new cycle of erosion, whether the previous cycle is complete or not. It appears to the writers, however, that there are practical, if not logical, advantages in regarding small changes of base-level as initiating sub-cycles or epi-cycles, which are essentially subdivisions of a major cycle of erosion. For this view at least two favouring arguments can be urged. First, since it has been credibly demonstrated that the cycle of erosion has passed to essential completion at many times and places, it has become, in some sense, a unit of time complementary to, and comparable with, the geologist's stratigraphical time units. We cannot, it is true, state its range of length in years, but the order of magnitude involved is sufficiently plain, and with the help of radio-active dating we may ultimately be able to measure roughly the duration of actual cycles in a particular region. If, then, the term "cycle" is also used for the vastly shorter periods which have elapsed between successive slight changes of base-level in recent geological times, we are using the same name for time periods of very different orders of magnitude. A second argument proceeds from the fact that the recent conditions of rapidly varying base-levels, falling within or just after a major

glacial period, are abnormal. The force of this consideration will appear in the sequel (pp. 422, 423). For these reasons we shall speak of the periods of time between "interruptions" as sub-cycles. A probable objection to such a course is that we have no right to think of cycles in terms of periods of time. While, however, this was a wise limitation in the days when the cycle concept was fighting for recognition, it should not now be insisted upon. The complementary records of erosion and deposition both mark the passage of time; and for both a quantitative basis should be persistently, if cautiously, sought.

Interruptions of the cycle of erosion may be brought about by movements of elevation or depression of the land itself. Such movements may affect large areas, but they are, nevertheless, in the broad sense, local—generally involving some element of bending or warping, resulting in an unequal change of base-level. Further, it is not probable that movements of the land in widely separated areas are rigidly contemporaneous. At least as important as such land-movements are movements of sea-level, brought about by change in the capacity of the ocean basins or by the waxing and waning of ice-sheets. Since the oceans are in full intercommunication such movements, termed eustatic (p. 52), are necessarily world-wide, and they must operate with virtual simultaneity over the whole area. The problem of the resulting changes of base-level is complicated, however. At first sight it might appear that the rise and fall of sea-level would be everywhere equal, but this is not literally true, for a eustatic shift of sea-level is probably always accompanied by some movement of the land (p. 421). We have seen that the crust sinks isostatically beneath an ice load and is uplifted as the load is removed. In broader terms we may say that the formation or dispersal of ice-sheets involves a redistribution of "load," which must affect the solid crust as well as the water envelope. It is equally true that any major change in the capacity of the ocean basins can only arise through some sort of earth-movement, and that eustatic movements so caused must be associated with some actual warping of the crust. Nevertheless, it may be considered likely that an eustatic change of base-level would maintain essential uniformity over much wider areas than one due primarily to land-movement.

In face of these complicated possibilities it is necessary to define the point of view of the geomorphologist and to

emphasize the fact that he is more concerned with results than with causes. The problems of the isostatic and elastic movements of the crust, and the eustatic movements of sea-level, are primarily matters for the geophysicist and the geologist. To the solution of these problems the evidence of geomorphology may make an important contribution. It can only do so, however, when the results of land-form study are correlated over wide regions. Pending such correlations, the student of land-forms may be wise to give the answer " Nescio " to the question of causes. Whatever be the *cause* of base-level changes, the *effect* in the local sphere is one of " uplift " or " depression." Since, however, these terms beg the question by suggesting that it is the land which moves, it is better to speak of depression as a " positive " (*i.e.* upward) movement of base-level, and of uplift as a " negative " (*i.e.* downward) movement of base-level. The sense of the terms may also be realized by remembering that, in general, positive movement marks an advance, negative movement a retreat, of the shoreline.

Results of a negative change of base-level.—A negative change of base-level gives rise to a complex chain of consequences. Rivers immediately begin to regrade their courses to the new sea-level, constructing a new curve, which, by headward erosion, progressively replaces the former curve. The junction of the two curves at any time is marked by a break of slope, which may be referred to as a " rejuvenation-head " or " knickpoint " (Fig. 132). The rate of upstream recession of knickpoints will evidently vary with the character of the rocks eroded, resistant rocks retarding the process. Thus, following the main episode of emergence which created the Atlantic coastal plain in the United States the rivers regraded their courses rapidly in the sediments of the coastal plain, and the first marked head of rejuvenation occurs near the line of junction with the underlying more resistant rocks, which build the Appalachians. Thus has arisen the Fall Line, or, more accurately, the Fall Zone of North America, where falls and rapids mark the descent of the streams from the " old-land " to the coastal plain.

Knickpoints, marked by falls or rapids, are readily recognized on many rivers, and have often been attributed simply to the influence of " hard rock-bands " (Fig. 89). This explanation misses a great part of the truth. In early youth, during general active degradation, all varia-

tions of rock-resistance tend to be reflected in the stream profile, but, with maturity, such inequalities disappear in large measure. After this stage is reached there is, short of considerable uplift and the initiation of an entirely new cycle, only one method by which knickpoints can be produced, viz. by small changes of base-level initiating " waves " of headward erosion. The recession of the resulting knickpoints will be retarded by " hard rock-bands " and, during any given interval of time, a majority of knickpoints will tend to be located on or near such outcrops. Others will show no such relation, however, nor will all the resistant rock elements cause breaks of profile. In brief, then, variation of rock-resistance is not the prime cause of knickpoints due to rejuvenation.

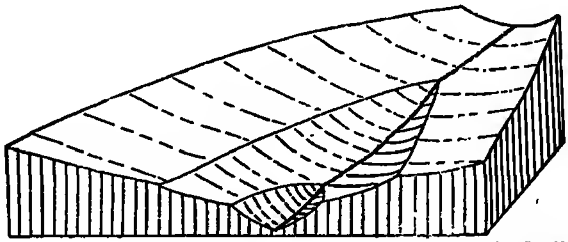
Examination of the profiles of rivers, particularly the tributaries of main streams, commonly reveals several knickpoints ; the profile curves are *composite* (Figs. 132 and 90). In such cases we have evidence of several successive stages of rejuvenation succeeding one another before the preceding attempts at regrading are complete. The preservation of such a composite curve seems at first sight to imply a sort of diminuendo in rejuvenation, each successive stage being less effective than the preceding one. This is not necessarily the case, however. A major phase of rejuvenation must normally obliterate the handiwork of all preceding minor stages, so that the composite, physiographic record can only retain traces of stages of regrading more advanced than any subsequent stage. Part of the record is inevitably lost.

The composite long-profile of rivers can frequently be correlated with composite transverse profiles, showing a series of distinct valley-side facets, separated by breaks of slope. The latter, like the knickpoints, are not necessarily related to structural features, though the extent of preservation of the " valley in valley " form varies with the character of the rocks. The relation of knickpoints to valley-side facets is illustrated in Fig. 132. In ascending such a valley each knickpoint marks the passage from a younger to an older valley segment, and the valley-side slopes become progressively gentler upstream. We evidently cannot assume that the upper and older portions of the valley have survived unchanged, since their development was first interrupted, but the changes have been relatively slow compared with those nearer the mouth, so that the broader features of older stages of the

landscape persist, pending the arrival of the knickpoint next downstream.

River Terraces

The conditions shown in Fig. 132 are those likely to be encountered in upland valleys cut in relatively resistant rocks, but it must not be supposed that knickpoints are always so diagrammatically obvious. With lowland rivers of generally gentle gradient, the breaks of profile can be detected in many cases only by accurate levelling ; it is



[*After Baulig.*

FIG. 132.—COMPOSITE VALLEY FORMS.

not sufficient to construct the profile from contoured maps. In such valleys, moreover, rejuvenation will commonly lead to the incision of the river course below aggraded flood-plains. In this fashion "paired" alluvial terraces are formed (Fig. 133 and 134).

River terraces are features of considerable geographical and geological importance. They afford dry ground on the valley floor, above the flood-plain, and commonly

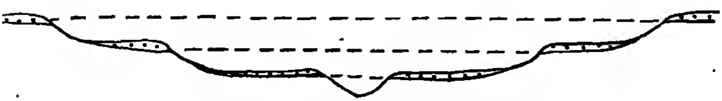


FIG. 133.—PAIRED RIVER TERRACES.

hold supplies of underground waters, so that they have figured prominently in localizing human settlement. Moreover, in the terrace deposits are found the fossil remains and stone tools of Palæolithic man. There is, in fact, a vast and complex literature on river terraces in their stratigraphical and archæological aspects. Their physiographic relations have not always been clearly comprehended, however. It is admitted that terraces can form in more than one way, but there is no doubt

that rejuvenation, in the fashion described above, is accountable for the terrace-sequences studied in many of the valleys of Britain and Continental Europe.

It is evidently important to define the relation of terraces to composite long-profiles. A relation commonly found in tributaries of main streams, and smaller valleys generally, is illustrated in Fig. 135. Starting in the lower part of the valley, the lowest terrace grades back into the flood-plain above the first knickpoint, and at each succeeding knickpoint the phenomenon is repeated. Below a knickpoint the corresponding terrace is necessarily discontinuous, since it is breached at tributary entrances and destroyed elsewhere by the lateral swinging of the rejuvenated stream. If sufficient relics remain, the construction of the terrace-profile may be a simple matter, but in the correlation of widely separated fragments the method initiated by O. T. Jones and J. F. N. Green is very valuable. We can calculate the approximate form of the curve from the surviving upper portion, and from any undoubted terrace remnants referable to the stage in question, and thus decide the allocation of doubtful remnants farther downstream. Pursuing the method further, we can estimate the level at which a tributary formerly joined its trunk, or in the case of a stream draining to the coast, the height of the former marine base-level. Thus, in the case of the River Mole, a considerable segment

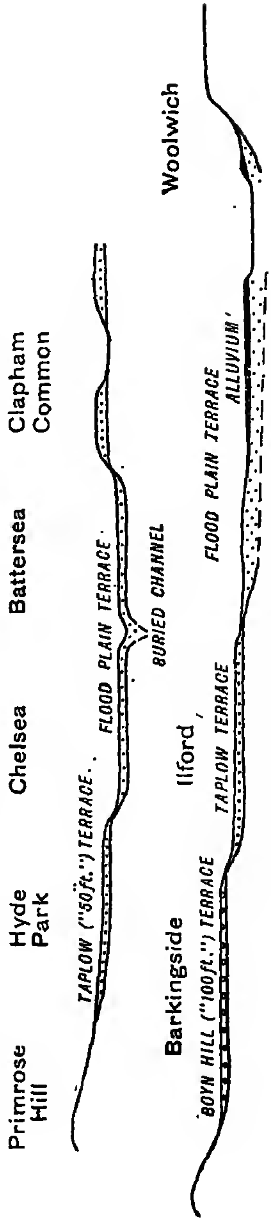


Fig. 134.—The Terraces of the Thames near London.

of the upper course is graded to the Boyn Hill or "100-foot" Terrace of the Thames, a fact demonstrated both by the calculated form of the curve in the upper river, and surviving terrace-remnants downstream. It should be noted that in such a case the upper portion of the curve has been somewhat modified by erosion and deposition, continuing after the abandonment of the terrace downstream, so that the reconstructed terrace curve cannot exactly fit the existing upper profile. Further, it is with the upper or terminal surface of the terraces, not their rock-floor, with which we are concerned in correlations of level, for these formed part of a former profile of equilibrium.

In larger rivers successive stages of regrading have progressed wholly, or in large part, to completion, so that terraces are virtually parallel with one another, and with

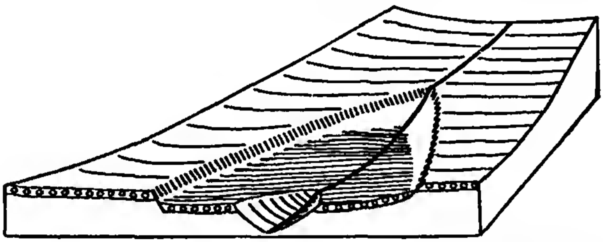
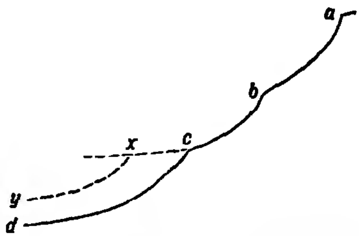


FIG. 135.—RELATION OF TERRACES TO COMPOSITE RIVER-PROFILE.

the present valley-floor, over long distances. Thus Chaput recognizes terraces continuous along the Loire for long distances, at elevations of 50 to 60 feet and 100 to 120 feet above the present flood-plain. Similar conditions exist in the lower Thames Valley. On the other hand, J. F. N. Green has noted cases in Southern Britain, typified by the Salisbury Avon, in which an upper terrace is left "in the air" by back-cutting at a lower stage (Fig. 136). The relations of terraces to profiles are therefore various and, since study on the above lines has only recently been undertaken, a full review must await the examination of many more actual cases. Meanwhile, it is clear that with composite river-profiles, confusion must result unless terrace heights are referred to Ordnance Datum, not to the height of the local flood-plain, as has often been done. Further, in correlation along the valley, it is, as already mentioned, the upper constructional surface of the terrace which should be considered.

The hidden terrace feature, cut in rock, also has its significance, as marking a prolonged phase of still-stand and lateral planation. With a composite profile, however, it cannot correspond with any features of the upstream profile, for the succeeding aggradation involves modification of this profile. The possible occurrence of exhumed rock terraces must, however, be borne in mind. Rock terraces might be expected to correspond with marine benches, or notches, cut in the contemporary coastline (p. 422), but many such features have been destroyed in later coastal evolution.

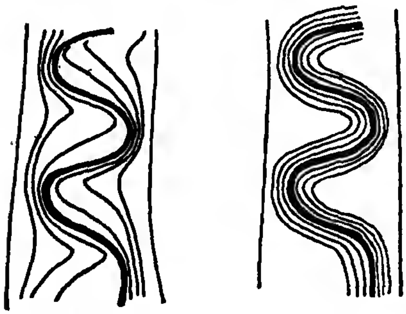


[After Green

FIG. 136.—COMPOSITE LONG-PROFILE OF RIVER.
Terrace XY has been overrun by back-cutting at stage CD.

Incised Meanders

The incision of meanders during rejuvenation leads to notable scenic effects, and is closely related to certain terrace features. When renewed down-cutting starts, meanders continue their changes in form and position, and the character of the resulting scenic forms depends, in part, on the relative rates of down-cutting and meandershift. Rapid incision gives rise to "intrenched meanders," of more or less symmetrical cross-section, while if the incision is less rapid, affording time for lateral shift, "ingrown meanders" result [1] (Fig. 137). The character of the rocks in which the incision takes place also has an

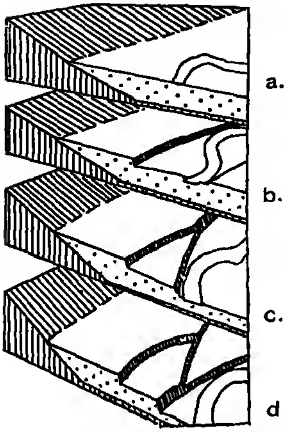


[After Rich.

FIG. 137.—INCISED MEANDERS.
(*a*) Ingrown. (*b*) Intrenched.

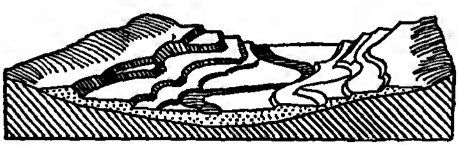
[1] The difference between intrenched and ingrown meanders reflects in some cases difference in the rate of "uplift," more rapid uplift favouring the intrenched condition. Since, however, the two types can co-exist within comparatively short distances along the same stream course, it is evident that rock character must also be an important determinant of meander-form. Relatively hard rocks, by retarding incision, may give time for lateral swing, and the development of ingrown meanders.

important bearing on the results. Consider first the case in which steady degradation is proceeding in a thick mass of unconsolidated river alluvia or glacial drift, filling the bottom of a valley. Meanders will migrate downstream, and each time the meander belt approaches the valley-side its floor is lower than on its previous visit and it may completely cut away the former flood-plain, or may leave a remnant as a terrace. The process is illustrated in Fig. 138. It will be clear that it may lead to formation of erosional terrace-surfaces cut in earlier alluvium, or other drift, at any level. Preservation of such terraces depends on the vagaries of meander-swing, and they have a totally different significance from the "paired terraces" described above. The latter represent a series of distinct phases of rejuvenation, after each of which regrading has achieved considerable headway. Erosion-terraces cut in drift reflect a continuous process. They are not paired across the valley, but tend to alternate in level from side to side. Unchecked meander-swinging during slow degradation would normally lead to almost complete destruction of all the temporary erosional terraces; but it has been pointed out that buried spurs and rock-bars laid bare in down-cutting or emergent



After Cotton.

FIG. 138.—DEVELOPMENT OF TERRACES BY MEANDER-SWINGING IN SOFT INFILLING OF VALLEY.

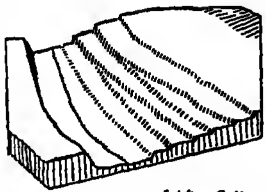


[*After Davis.*

FIG. 139.—TERRACES PROTECTED BY ROCK-LEDGES, CORRESPONDING TO BURIED SPURS.

rock-ridges through which the stream cuts in gorges, form fixed nodes on the river's course, near which the meander-swinging is restricted. In the vicinity of such points the "flights" of erosional terraces tend to be fairly complete. (Fig. 139).

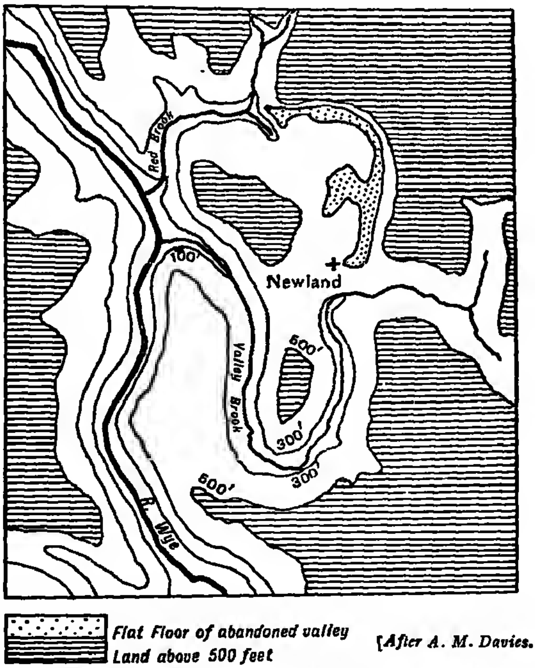
The incision of meanders in coherent rocks also gives rise to varied effects. If, with major meanders of ingrown type, the lateral shift is slow and long continued, it may extend over several minor periods of rejuvenation. In such case a flight of terraces may mark the "slip-off slope" of the developing meander (Fig. 140), each corresponding to a phase of aggradation on the outer edge of the curve, leaving the former flood-plain largely intact. This phenomenon is well seen on the Thames near Radley, though the terraces are far from continuous. It will clearly tend to occur wherever uniclinal



[*After Cotton.*

FIG. 140.—FLIGHT OF TERRACES ON SLIP-OFF SLOPE.

The terraces have been abandoned in course of uniclinal shifting or meander development.



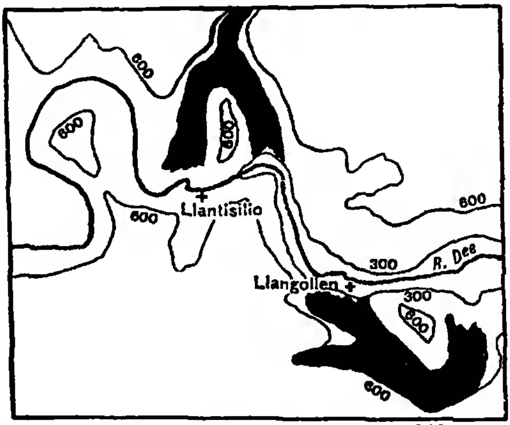
[*After A. M. Davies.*

FIG. 141.—THE NEWLAND ABANDONED INCISED MEANDER AND MEANDER CORE.

(Scale 1 in.=1 mile approx.)

shifting, of whatever cause, operates during rejuvenation. Spectacular results ensue from the abandonment of incised

meanders, following "short-circuit" cuts through spurs. In its essence the process does not differ from the short-circuiting of flood-plain meanders, but the results are more marked and permanent. As in the latter process, the broadening of meander-heads to a "fan-tail" form narrows the bases of the spurs until a break-through occurs. Excellent examples of the results of this process have been described by A. M. Davies from the Wye Valley and elsewhere (Fig. 141). The abandoned loop remains as an arcuate valley, dry in its central parts, but draining from its ends to the river. The floor of the central portion stands well above present river-level, since down-



[After Wills.

FIG. 142.—ABANDONED INCISED MEANDER, PLUGGED WITH GLACIAL DRIFT, NEAR LLANGOLLEN.

Drift plugs shown in black. (Scale 1 in.=1·5 miles approx.)

cutting has since continued. The severed spur, or *meander core*, remains as an isolated conical or flat-topped hill. There is no reason to doubt that these effects can arise in the normal course of river-erosion, particularly in regions of well-jointed limestone rocks where it may be assisted by underground solution (p. 291). The intermediate stage, in which a natural bridge crosses the cut-through, is known in such limestone regions. On the other hand there is little doubt that the abandonment of incised meanders has often been assisted, if not brought about, by the plugging of portions of the original looped course by ice or glacial drift. This was certainly the case for the great abandoned loops of the Dee near Llangollen (Fig. 142).

CHAPTER XVI

DENUDATION CHRONOLOGY: SOME EXAMPLES

In the following pages we shall seek to summarize and exemplify the principles indicated in the last chapter by reference to certain areas of which the morphological history can be reconstructed, in outline at least. Such reconstructions form the last chapters in the geologist's volume of records, the processes of landscape-shaping overlapping in time with the later depositional episodes. Equally, they form the preface to the geographer's work, in which the landscape is the background of human occupancy.

The Appalachian region.—The Appalachian region of the Eastern United States claims our attention, not only for the intrinsic interest of its geological history and present land-forms, but because it has been the scene of classic work in geomorphology. The work of W. M. Davis, on the drainage of Pennsylvania and of New Jersey, extended and gave precision to the basic ideas worked out by Gilbert and others in the west; it is a veritable landmark in the history of the subject. Later work, particularly that of D. W. Johnson, has opened up some of the questions anew and led to the building up of a connected scheme of evolution for the whole area. For us, not the least interesting aspect of Johnson's work is the evident analogy of the conditions he portrays with those holding in Europe at about the same time.

The original Appalachian Mountains were raised by the crumpling and upheaval of a great geosynclinal tract towards the end of Palæozoic time. East of the geosyncline (Fig. 143) lay a considerable land-mass, probably extending far beyond the present American coast, and called by American geologists "Appalachia." From this land-mass much of the sedimentary infilling of the geosyncline was derived. Westwards of the geosyncline shallow seas spread over the region of the present Mississippi lowlands. In the course of the orogenesis the western border of Appalachia, consisting of ancient crystalline rocks, was driven against, and partially over, the thick sedimentary pile to the west, which was thrown

into close-spaced parallel folds. Beyond the western border of the geosyncline, where the sedimentary cover was thinner, the disturbance of the rocks was much less marked (Fig. 144).

In the belt of intense folding we can, very roughly, reconstruct the form of the original folded surface, by projecting upwards and completing the structures of the present surface. In the nature of the case such reconstruction cannot be accurate, but it suffices to give some rough measure of the vast changes in landscape which have since occurred. In the present structure and morphology of the region we note the following zones succeeding one another from west to east (Fig. 145):—

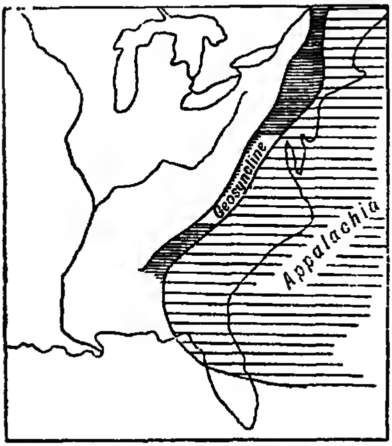
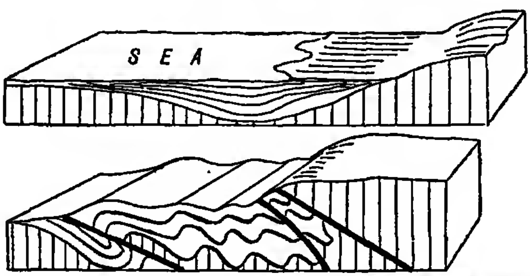


Fig. 143.—The Appalachian Geosyncline.

(*a*) The Allegheny plateau of flat-lying or little disturbed Palæozoic sediments; this represents the western marginal area of the original geosyncline.

(*b*) The " Newer Appalachians "—the zone of intensely folded Palæozoic sediments corresponding with the original



[*After Longwell, Knopf and Flint.*

Fig. 144.—The Appalachian Orogenesis.

The lower diagram shows the folding and faulting of the rocks accumulated in the geosyncline shown in the upper diagram.

geosynclinal belt. To-day we see merely the roots of the former mountain chain. The Newer Appalachian zone extends from the St. Lawrence Valley to Alabama. On

the whole, it is marked by relatively low ground, but throughout its length, and particularly in Pennsylvania

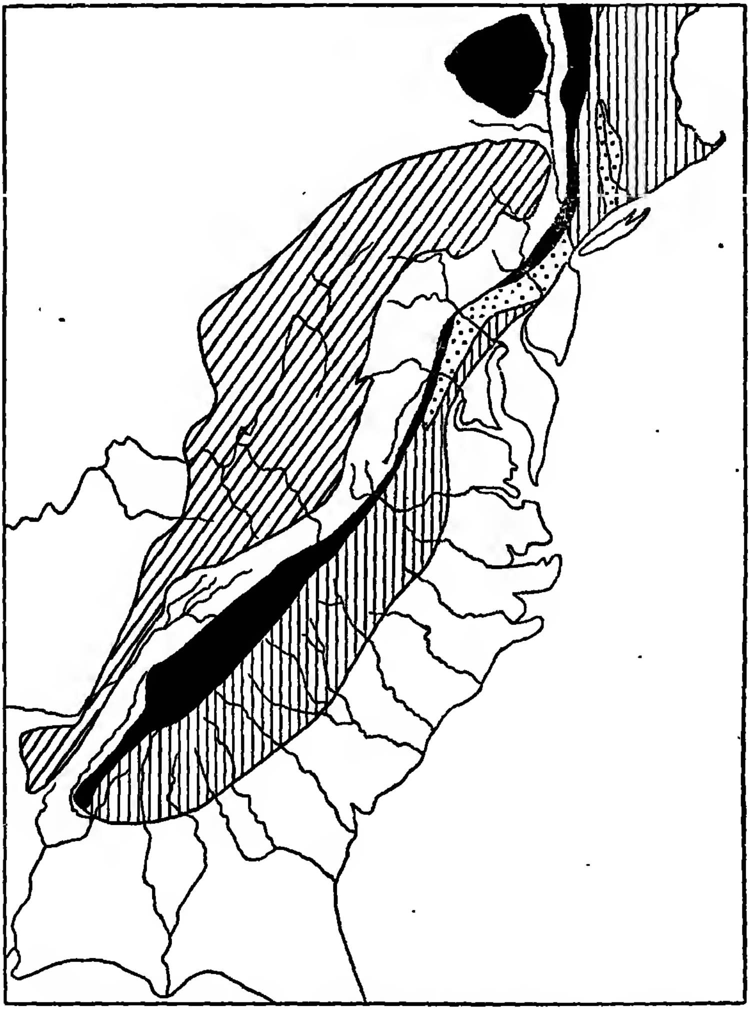


FIG. 145.—THE STRUCTURAL REGIONS OF THE APPALACHIANS.

In order from east to west: Coastal plain=white; Piedmont and New England plateaux=vertical shading; Triassic belt=dots; Blue Ridge and its continuations=black; Folded belt (Great Appalachian Valley)=white; Allegheny plateau=oblique shading.

and Virginia, the resistant rock-elements stand in sharp-crested, level-topped ridges, separated by subsequent or

resequent vales excavated in weak rocks (limestones and shales).

(*c*) The "Older Appalachians"—a zone of ancient crystalline rocks representing the western border of Appalachia. In the south this zone embraces the low Piedmont plateau; while in the north it is represented by the New England upland. In both regions the western border is elevated, giving the Blue Ridge and its variously named continuations in the south and the Taconic Range, White Mountains, etc., in New England. Strips of Palæozoic sedimentary rocks are locally faulted down into the crystalline mass, and being less resistant have been etched out as subsequent troughs. Between its maximum developments in the southern and northern regions, the old crystalline zone narrows markedly, and a lowland floored by infaulted Triassic rocks is included within it in the New Jersey region.

(*d*) The Atlantic coastal plain, which consists of Cretaceous and post-Cretaceous sediments resting on the buried floor of crystalline rocks and dipping gently seaward. The boundary of this zone and the Piedmont is marked by the Fall Line (p. 220).

The relation of the drainage to these several structural elements varies considerably from place to place, though certain underlying elements of unity are discernible. In the south the main water-parting is the Blue Ridge, from which streams flow west to the Mississippi Basin and south-east or south to the sea; and in the Newer Appalachian zone there are important and continuous longitudinal or subsequent elements in the drainage. In the north the main water-parting is at the Allegheny Front, the great escarpment which marks the eastern limit of the plateau; from this line rivers flow westwards to the Ohio and eastwards across all the structural zones of the region to the Atlantic coast; in the Newer Appalachian zone the transverse rivers receive important subsequent tributaries, but subsequent drainage is less dominant than in the south.

The sequence of events by which the present drainage system came into being has been variously interpreted. Confining our main attention to the Northern Appalachian region, where most of the detailed investigation has been done, we may note the following facts which have to be reconciled in any acceptable solution of the problem.

1. The reconstruction, by upward projection of present structures, of the original form of the folded Appalachian ranges suggests that the original main drainage lines must have been directed towards the west.

2. The existing main drainage is directed towards the south-east, crossing the ridges of both the Newer and the Older Appalachians. The accordant summit-level and bevelled form of these ridges show clearly that the region was reduced to a condition of low relief and then uplifted, with trenching of the drainage across the revived ridges. The summit-plane of the New Jersey region is referred to in the literature as the Schooley peneplain, being well developed on the flat top of Schooley Mountain east of Hackettstown (Fig. 146).

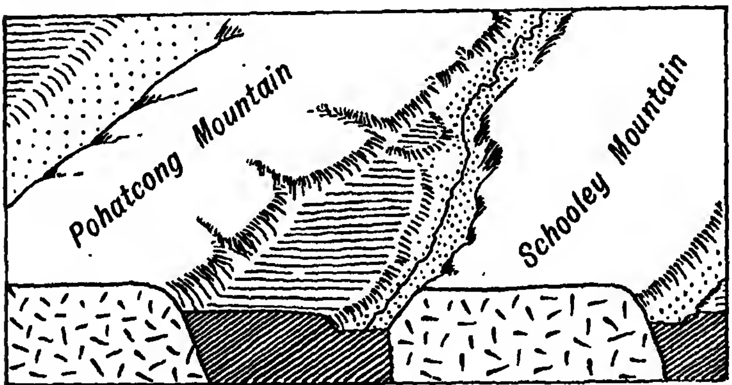


FIG. 146.—THE SCHOOLEY PENEPLAIN.

3. Some, at least, of the divisions of the coastal plain sediments must formerly have extended westwards beyond their present limits; and to some extent, therefore, the existing drainage must have been superimposed from the coastal plain cover, which rests on a peneplained surface, itself tilted, like the overlying beds, towards the coast and emerging from beneath the cover over a limited zone near the Fall Line (Fig. 147). This surface has been termed the Fall Zone peneplain.

4. The drainage systems of the region, as a whole, show a very perfect adaptation to structure. The infolded weaker elements of the Newer Appalachians and the similar infaulted strips in the older crystalline mass are all coincident with well-developed subsequent or resequent

valleys. Wind-gaps in the ridges attest the occurrence of river-capture, since the uplift of the Schooley peneplain, *i.e.* in the post-Schooley cycle. There are also cases of apparent diversion of consequent drainage *not* marked by wind-gaps, and therefore to be referred to a " pre-Schooley cycle " (p. 211).

For the greater part, these facts form common ground for all those who have studied the subject, but opinions have differed on two questions of outstanding importance, viz. the former inland extent of the coastal plain cover, and the identity or otherwise of the Schooley and Fall Zone peneplains. Davis, in his pioneer works, assigned a very limited former westward extension to the coastal plain cover. Further, he assumed that such extension was over the surface of the Schooley peneplain, which he treated, therefore, as the inland continuation of the Fall Zone peneplain. His picture of the conditions immediately precedent to the initiation of the present relief-forms thus involved one peneplained surface, covered with Cretaceous deposits over a limited area on its eastern side, but for the rest a Cretaceous land-surface. In Pennsylvania he derived the existing drainage by an ingenious, but complex, reversal of the original westward drainage, without assuming any former coastal plain cover in the region. In New Jersey he assumed the presence of such cover only in the eastern part of the region.

While the interpretation given by Davis affords a credible picture of the drainage as a whole, there are certain general characteristics and particular features of the drainage system for which it fails to account. In 1928 D. W. Johnson announced an alternative hypothesis, since developed more fully, which, while set forth with studied moderation and fairness to alternative views, will certainly carry a large measure of conviction to many. In essence, it involves a former great inland extension of the coastal plain cover across a surface higher and older than the Schooley peneplain—none other, in fact, than the Fall Zone peneplain. He thus envisages regional superimposition of the drainage near the beginning of the cycle which culminated in the Schooley peneplain. The elements of this hypothesis will be readily gathered from Fig. 147. We cannot here treat in full of Johnson's long and closely reasoned argument, but we may briefly indicate the type of evidence used and the general conclusions reached.

The evidence favouring Johnson's hypothesis derives from a wide field. A first essential point is the establishment of the existence of two separate peneplains intersecting in the vicinity of the Fall Line. Work by Renner contributes to the support of this conclusion. Not only is the angle of intersection sharp, where favourably preserved and exposed, but it is continuous for long distances. An hypothesis which makes the two surfaces continuous across a line of warping, involves the coincidence of such a line with the inner edge of the present coastal plain for hundreds of miles. Such a relation would be almost impossible to explain. Moreover, it can be shown, by the evidence of borings, that the steep slope of the Fall Zone peneplain in its region of emergence is not a local feature due to monoclinal bending, but is continued seawards beneath the cover. Further, it may be noted

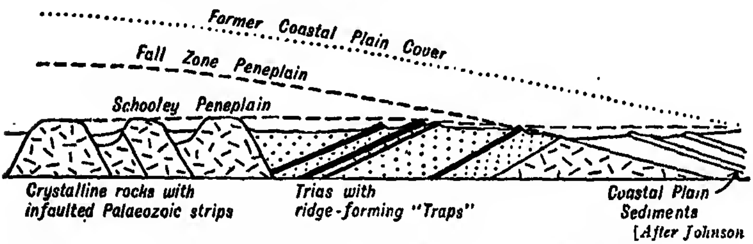


FIG. 147.—RELATION OF SCHOOLEY AND FALL ZONE PENEPLAINS.

that proved remnants of Cretaceous beds are absent from the Schooley surface, but are present as outliers on the emergent portion of the Fall Zone surface. A further pertinent general consideration may be added : on general grounds it is unlikely that a Cretaceous surface, even if protected for a time by a sedimentary veneer, would be so well preserved as the Schooley surface, which survives undissected over appreciable hill-top areas.

Granting, then, the separate existence of the Fall Zone peneplain, its proved great extension from north-east to south-west would strongly indicate, if it did not prove, a correspondingly great inland extension. It would not necessarily follow that the coastal plain cover extended so far ; this is a different question. Nevertheless, such wide inland extension is a reasonable assumption. The lithology of some of the coastal plain sediments has been held to indicate accumulation near a shoreline, but this is certainly not true of all of them. There was time

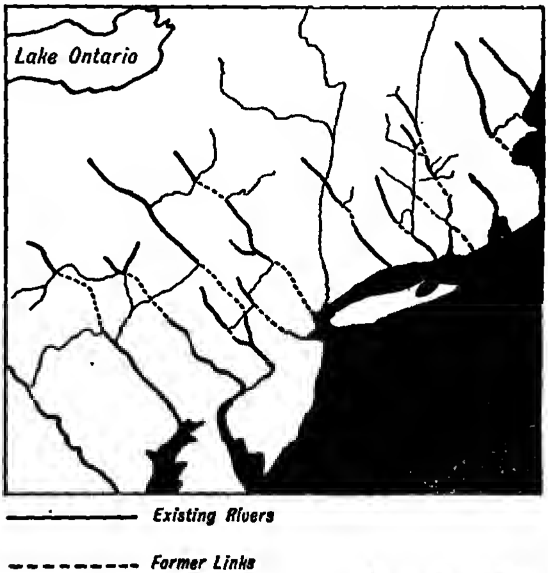
and space for greatly varying conditions of transgression, and it is evident that a small change of level would produce a large shift of strand-line over the uniform Fall Zone surface. However, all that the stratigraphical geologist is likely to concede is that certain elements of the cover *may* have had a considerable westward extension. The only direct evidence comes from geomorphology. The present drainage system shows evidence of being superimposed (see below). Only thus can we account for the obliteration of an earlier drainage, probably on a very different plan. If superimposition did not take place on the Schooley surface, it must have taken place earlier, and this renders a former wide extension of the coastal plain cover at least very probable.[1]

As regards the features of the actual drainage system, Johnson has found it possible to reconstruct the simple lineaments of what was probably the original consequent system, by joining up aligned reaches of the existing transverse rivers, using linking wind-gaps where they exist. The system comprises streams of south-easterly direction (Fig. 148), notably parallel with one another, but oblique to the " grain " of the present land-surface. Such a system points to regional superimposition from a surface of initially simple form. Fig. 148 shows that the early lines have been broken up by the development of subsequent streams, leading to river capture. The high perfection of adjustment to structure bespeaks a long period of adjustment. It could hardly have been accomplished if the drainage had been superimposed directly on the Schooley surface. Superimposition under the condition shown in Fig. 147 would effectively double the " vertical range " available for adjustment, leaving the " post-Schooley cycle " merely to finish what the " pre-Schooley cycle " had begun.

A converse application of the same argument leads us to perceive that direct superimposition on the Schooley surface should have left the consequent lineaments of the original drainage plainly marked, or easily reconstructed. In such a case the diversion of consequent streams would have taken place largely in the " post-Schooley cycle,' and, to borrow the language of examiners, would have

[1] It will be noted that in this case an argument drawn from morphological considerations points independently to an essentially geological conclusion—the extension of former seas. A similar argument is applicable in many other regions and, used with due caution, promises important help to the geologist in the difficult task of placing former sea-margins.

" left evidence of the methods employed " in the form of wind-gaps. In point of fact, taking the North Appalachian province as a whole, the original consequent drainage cannot easily be reconstructed. The adjustments of the post-Schooley cycle are plainly engraved on the landscape, but there were others which took place above the present hill-top plane and which presuppose, therefore, a former period of adjustment. The required conditions are adequately supplied by the hypothesis of regional superimposition.



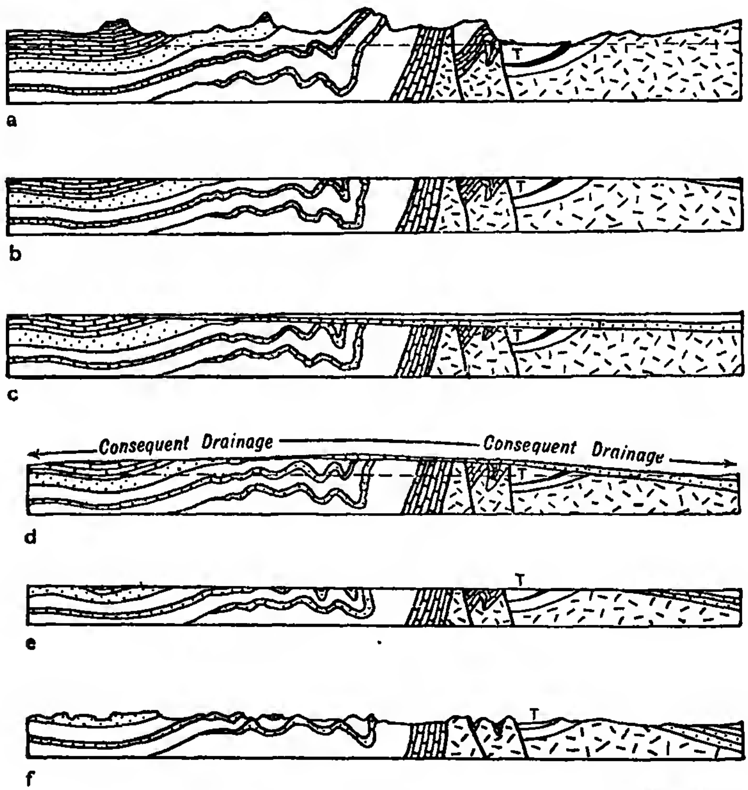
(After Johnson, simplified.

FIG. 148.—THE CONSEQUENT LINEAMENTS OF THE NORTH APPALACHIAN DRAINAGE.

The thin lines in general mark subsequent streams.

The general succession of events as conceived by Johnson is represented in Fig. 149, which shows cross-sections, successive in time, across the Appalachian belt in about the latitude of Philadelphia. In the first stage (Section (*a*)) we see the Appalachian Mountains in early Mesozoic times. It is possible that even before this stage they had suffered extensive planation, but were revived, following the movements which in-faulted the Triassic beds, seen towards the right of the section. Section (*b*) shows the results of complete planation in later Mesozoic times.

The surface indicated is the Fall Zone peneplain, and on this surface the drainage may well have been largely longitudinal, parallel with the former mountain ridges. In Section (*c*) the transgression of the Cretaceous sea is shown extending right across the area and effectively obliterating all traces of earlier drainage. Section (*d*)



[*After Johnson.*

FIG. 149.—STAGES IN THE DEVELOPMENT OF THE NORTH APPALACHIAN LANDSCAPE.

shows the up-arching of the region, with initiation of the present drainage on the constructional slopes. In the next stage (*e*), a cycle of erosion has run its full course. The drainage has been superimposed from the cover and has then cut down much farther, producing another peneplain—the Schooley peneplain. With uplift—combined, probably, with slight arching—of the latter, the

current major cycle was initiated; former ridges have been revived and former lowlands re-excavated (Section (*f*)). In detail, the record of the current cycle has been punctuated by several well-marked stages of partial planation, *i.e.* planation on the weaker rocks. The surfaces in question have been termed peneplains, but from the standpoint here adopted they hardly justify this name; they are platforms marking stages in the excavation of the longitudinal lowlands, and perhaps in part true panplanes (p. 186).

The drainage systems of Britain.—We have already noted (p. 198) the broad analogy between the structure of Eastern North America and that of the English Plain and its western borders. It will now be seen that there may well exist considerable analogy between the denudation-chronology of the two areas. Many workers have been led to the conclusion that the British drainage must have been initiated on a cover of Chalk (Upper Cretaceous) tilted towards the east and south-east, and formerly extending over much of the present upland areas of Western Britain. We have mentioned the well-developed summit-plane of Wales, and it is apparent that this feature occupies in some sense the position of the Schooley peneplain in the American problem. It might, conceivably, represent the basal Cretaceous surface, or alternatively, it might mark the close of a later cycle of erosion, the Chalk cover having passed originally high above it. In several respects, however, the problem is more difficult in Britain, despite our comparatively detailed knowledge of the geological history of the area. For this there are two chief reasons. In Southern Britain the Cretaceous cover is nowhere superimposed directly on the older Palæozoic rocks, such as form the western uplands. Over much of the area a great thickness of Triassic and Jurassic rocks intervenes between the present Chalk edge and the upland border. The Chalk approaches closest to the latter in Devonshire, but even there it is a difficult matter to relate the westerly projection of its basal plane to the morphology of the upland province. In general, we are confronted with the prior question of the extent of overlap of the Triassic and Jurassic rocks over the western massifs. A second complication arises from the fact that in South-east England land-forms and drainage are plainly related to an episode of pronounced folding—the "outer ripples of the Alpine storm"—which occurred in Middle Tertiary

times. No such strong localized folding occurred in the eastern part of the United States. Moreover, we are in considerable doubt as to the extent to which the mid-Tertiary folding affected the rest of Britain. Its major effects are seen south of the Thames, but there may have been significant warping in areas farther north.

In these circumstances we shall find it best to consider first the drainage of the English Weald, lying in the region affected by the most recent folding, and flanked by surviving outcrops of Tertiary deposits which mark the last submergences of Britain. For this region we can construct a broadly complete chronological picture of drainage development, and we may then apply our findings over a wider field.

The drainage of the Weald.—The area known as the Weald is, from the structural point of view, a complex elongated dome whose longer axis extends from Hampshire to the Sussex coast near Hastings, and may be traced beyond the English Channel in the Boulonnais. As commonly represented in cross-section the structure of the Weald is over-simplified; while the broad domed form is an important feature, a considerable number of subsidiary folds can be distinguished running parallel with the main axis. In addition to these longitudinal folds, there are broader, gentler flexures transverse to the main axis which have played no small part in the evolution of the relief. In its present state of dissection the dome appears with its central higher part entirely removed (Fig. 153*d*). The Chalk forms a well-developed escarpment on the north, west and south of the area, and the ring is completed in the Chalk hills which bound the Boulonnais. A much less continuous and uniform escarpment is formed by the Lower Greensand, whose thickness and hardness vary considerably within the region. The axial tracts are occupied by a broad dissected upland sited upon the outcrop of the Hastings Sands series. Two main strike-vales intervene between these three uplands. One, relatively narrow, is sited upon soft sands and clays which intervene between the harder parts of the Lower Greensand and the Chalk, while the other and broader vale coincides with the outcrop of the thick Weald Clay series.

The main streams of the Weald are evidently consequent, and may be conceived as having originated upon the initial flanks of the dome. They form two sets, draining the

northern and southern flanks of the dome, respectively; the Stour, Medway, Darent, Mole and Wey on the north, and the Cuckmere, Ouse, Arun and Adur on the south (Fig. 150). These main consequent streams have cut striking gorges or water-gaps through the Chalk escarpment. The corresponding gaps in the Lower Greensand ridge are not so conspicuous, since the Greensand will not as a rule stand in such steep slopes as the Chalk.

The tributaries of the consequent streams clearly reveal in many cases their subsequent character, flowing along the strike-vales mentioned above. Particular mention

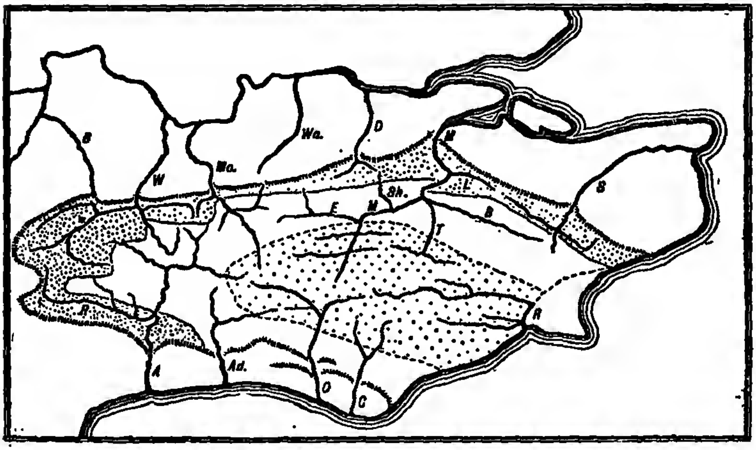


FIG. 150.—THE DRAINAGE OF THE WEALD.

B, Blackwater; W, Wey; Mo, Mole; Wa, Wandle; D, Darent; M, Medway; S, Stour; L, Len; B, Beult; T, Teise; Sh, Shode; E, Eden; R, Rother; A, Arun; Ad, Adur; O, Ouse; C, Cuckmere.

may be made of the subsequent Rother, tributary to the Arun, sited upon one of the softer elements in the Lower Greensand series. In a similar geological situation we find the Len, tributary to the Medway, the Great Stour and East Stour, which join to form the main consequent trunk of the Kentish Stour at Ashford. In the Weald Clay vale the best developed subsequent streams are the Eden and the Beult, which drain eastwards and westwards, respectively, into the Medway. In the Central Weald the rivers also show a marked longitudinal arrangement, flowing parallel with the geological grain. As already noted, they are here largely resequent in relation, occupying synclinal valleys.

River-capture

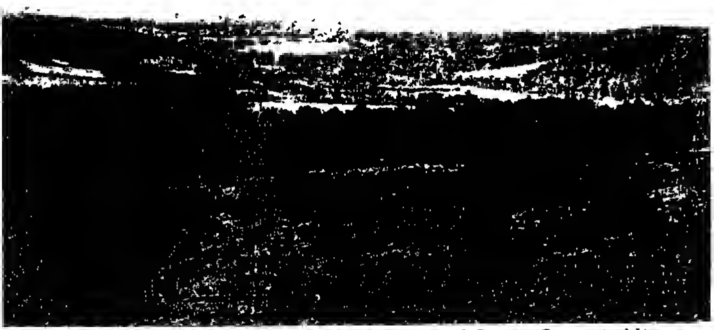
Instances of river-capture are readily recognized. It is evident that the headwaters of the Medway in the Central Weald once formed the head of the Darent system. They were appropriated by a subsequent stream developing westwards from the main Teise–Medway trunk. The River Shode is the reversed obsequent stream which now drains southward through the gap in the Greensand ridge, formerly occupied by the northward flowing Darent. The present stream which bears the name of the Medway is therefore composite in origin, comprising a lengthy subsequent stretch on the Weald Clay and a lower consequent portion continuing the line of the River Teise. In a similar fashion the Wey has beheaded the Blackwater, and a striking wind-gap remains near Aldershot as a testimony of the former existence of a continuous river channel draining northwards. The Wey, in its turn, has obviously suffered from the depredations of the Arun, which now heads, far north of the main anticlinal axis, on the southern slopes of the Lower Greensand escarpment. It has thrust its way in on both sides of the consequent trunk of the Wey, and has thus reduced the drainage area of the latter to insignificant proportions. This capture differs somewhat from the others quoted, in that it concerns the struggle for existence of two consequent streams flowing in opposite directions. Another example of the more normal type is the beheading of the Wandle by the Mole, which is marked by wind-gaps at Merstham and Caterham and by a well-developed obsequent stream flowing southwards through Redhill. Many other examples of capture occur within the area, but they are difficult to demonstrate upon a map of small scale. There are prominent wind-gaps in the Chalk escarpment at Cocking (north of Chichester), at Findon (north of Worthing), at Jevington (near Eastbourne), and at Lyminge (near Folkestone). The floors of all these gaps, together with that at Merstham, occur at about the same level (350 to 400 feet), showing that the several captures took place at about the same stage in the down-cutting of the valleys.[1]

[1] The physiography of the South Downs area may be studied from the "Chichester" and "South Downs" tourist sheets of the Ordnance Survey. A portion of the North Downs area is effectively shown on the "Dorking and Leith Hill" sheet of the same series.

[Photo by H.M. Geol. Survey. Crown copyright reserved.

FIG. 151.—TWIN WATER-GAPS IN THE CHALK RIDGE AT CORFE, DORSET.

View looking south from Middlebere Heath. Two streams flowing across the Lower Cretaceous rocks behind the ridge, unite north of it and flow as a single stream over the Eocene outcrop in the foreground.



[Photo by H.M. Geol. Survey. Crown copyright reserved.

FIG. 152.—THE MOLE GAP IN THE NORTH DOWNS, LOOKING NORTHWARDS FROM LEITH HILL.

Earlier cycle of erosion

The high degree of adjustment to structure shown by the drainage of the Weald suggests, even on casual inspection, that the region has passed through more than one cycle of erosion. The following considerations emerging from more detailed study confirm this idea :—

1. The hill-tops show a generally accordant summit-level, suggestive of a former peneplain. The culminating points of the North and South Downs just exceed 800 feet in height, the Lower Greensand summits in the Western Weald are about 900 feet in height, while the central upland reaches 780 feet at its highest point—Crowborough Beacon.

2. The Chalk escarpment shows signs of distinct bevelling in places, thus retaining some portions of a summit-plane virtually intact.

3. The general straightness of the escarpments may be regarded as inherited from the preceding phase of planation. The consequent streams are at present cutting salients in the escarpment, but have so far made little progress in the task (p. 202).

4. The general absence of flint (derived from the Chalk) in the river deposits and surface soils of the Central Weald indicates the stripping of the Chalk from the area during a preceding cycle. There has been no source of flint within this central region during the excavation of the present valleys.

General summary of the physiographic evolution of the Weald

Much further evidence bearing upon the evolution of the Weald is afforded by a study of the geological history of neighbouring tracts. It is not appropriate to deal fully with this aspect of the question here, but a brief sketch of the later history of the area may be given.

The uplift of the dome started before the accumulation of the Chalk was complete, for the various divisions of the Chalk become thinner as they are traced towards the central area, thus giving evidence of a rising sea-bottom with greater wave or current erosion in the central tracts. Thereafter, the whole region emerged from beneath the sea as the result of a broad uniform uplift. It remained a land area for a considerable period and suffered some measure of sculpture and lowering during this time. It is probable that the initial surface after uplift was

essentially featureless, and the amount of erosion which took place is difficult to gauge. Probably, however, we are justified in regarding the interval as a complete cycle of erosion, for the culminating form was certainly a rolling lowland of the peneplain type. At this stage, however, the Chalk still stretched unbroken across the axial region, although its upper parts had no doubt been removed.

The next phase in the history marks the re-submergence of parts of the region and the accumulation of the Tertiary beds, which now occupy the flanking areas—the London and Hampshire Basins. These deposits, of which the familiar London Clay is the chief, once extended far beyond the confines of their present outcrops. They may have been originally continuous across the western end of the Wealden uplift and over the Salisbury Plain area, but there are good reasons for believing that the central Wealden tracts projected as an island above the Tertiary seas (Fig. 153*a*). Many flint pebbles were worn from its shoreline, and we may imagine a series of short rivers diverging radially from the axial tract and flowing to the surrounding sea. It is clear that at first the valleys of these streams cut through nothing but Chalk, but with the passage of time some of them cut down through the Chalk cover, for they carried small pebbles of Lower Greensand material into the Tertiary sea.

Following upon this phase of deposition there came the main episode of uplift and folding in the area, broadly coincident in time with the building of the Alps, and responsible for the chief structural features of the Weald as we see it to-day (Fig. 153*b*). It is to this date that the imposition of the general domed structure is to be referred, and the various subordinate folds date from the same period. It is to this uplift, moreover, that the initiation of the main consequent streams is due. It is significant that they conform to the shape of the broader dome, rather than to the plan of the minor longitudinal folds. This may imply that the general doming preceded the minor buckling, and that accordingly the main consequent streams were antecedent to the longitudinal folds. Alternative explanations present themselves, but the question is difficult and need not be pursued here. The uplift certainly initiated a cycle of erosion which ran its full course, and produced a peneplain which cut indifferently across the several formations (Fig. 153*c*). No doubt the axial tracts continued to stand somewhat higher than the

margin, but the general flatness of the peneplain surface is sufficiently attested by the accordant summit-levels of the present higher hills. The Chalk had by now been removed from the central tract and the surface constituted a belted outcrop plain. Considerable adjustment to

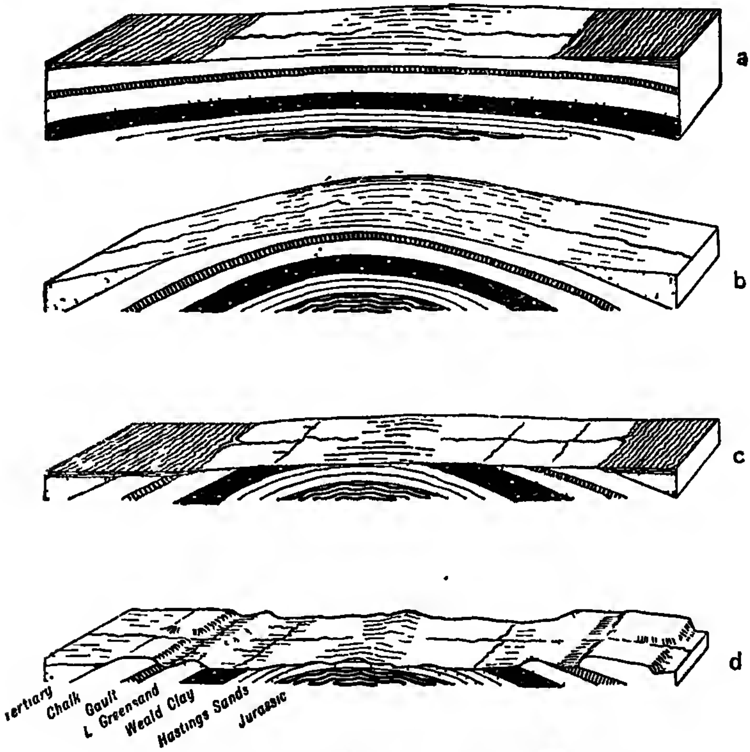


FIG 153—STAGES IN THE EVOLUTION OF THE WEALD.

(*a*) Early Tertiary (Eocene) phase with sea on both sides of the central ridge or island (cf Fig 113) (*b*) Middle Tertiary phase—main uplift of the Weald, contemporary with the Alpine mountain building (minor folds omitted) (*c*) Late Tertiary phase (Miocene and Early Pliocene)—peneplanation followed by advance of Pliocene sea (*d*) Uplift and dissection of peneplain and continuing marine bench, with evolution of present relief forms

structure undoubtedly took place during the cycle. The number of consequent streams was probably largely reduced in its early stages, and the growth of subsequent and obsequent tributaries was far advanced. In the Central Weald the fold-guided drainage had passed through its normal succession of phases, and the longitudinal

streams had come to occupy synclinal positions in many cases.

The record was interrupted at this stage by the submergence of the northern parts of the area beneath the Pliocene sea and the spreading out of a thin sheet of sand and shingle over the peneplain, after a certain trimming of its surface by the waves. This sea did not, however, extend over the central tracts, and its incursion hardly affects the general course of land-form development.

The next important event was the elevation of the whole area to the extent of about 600 to 800 feet. Coupled with the general uplift there was some re-doming of the area, much slighter in character than in the main episode of folding. The general uplift took place in several stages, separated by lengthy pauses during which the strike-vales were cut down by river action. These details need not here concern us; the main result of the uplift was to cause the re-incision of the streams in their old courses and the revival of the escarpments. It is easy to form a rough estimate of the amount of escarpment recession in the present cycle by projecting the base of a dipping stratum until it cuts the reconstructed surface of the former peneplain. In the course of down-cutting further adjustment of drainage to structure has taken place. The river-captures mentioned above have clearly occurred in the *present* cycle, since they are marked by wind-gaps in existing ridges. Peneplanation has proceeded apace on the outcrops of the softer beds, which have already been reduced to lowlands; but, taking a general view, it is evident that the cycle has not got beyond the stage of maturity, and has a lengthy course yet to run.

Denudation chronology in other British areas.—The sequence of events in the Weald affords us a rough scale of time by which the progress of denudation over the rest of the country can be estimated. We have concluded that a full cycle of erosion ran its course after the mid-Tertiary folding movement, producing a peneplained surface still recognizable in the Wealden summits. Outside the area of folding we have no clear evidence of the extent or character of the mid-Tertiary movements, yet there is little doubt that considerable movement did occur. We might, therefore, expect to find a summit-plane corresponding to the Wealden peneplain, and marking the end of a cycle of erosion initiated by the same mid-Tertiary movements. It would, however, be too large an assumption

that any summit-plane in Central or Northern Britain necessarily represented the Wealden peneplain surface. We must rather attack the problem from the other end, reconstructing the probable original lines of consequent drainage, and noting evidences of adjustment to structure, before postulating any succession of cycles.

Two major probabilities assist the inquiry. In the first place, as already noted, there is every reason to believe that it was on a Chalk surface that the drainage of much of Britain was initiated. The Chalk was certainly one of the most extensive of the later Mesozoic formations. It exists in outlying masses in Antrim and Western Scotland,

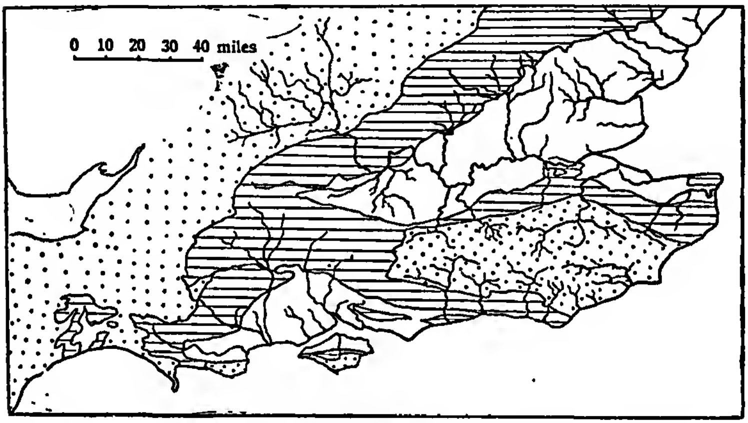


FIG. 154.—THE DRAINAGE OF SOUTH-EAST ENGLAND.

Tertiary rocks=white; Chalk=horizontal shading; Lower Cretaceous and Jurassic rocks=dotted.

far beyond its main escarpment, and it is probable that it formerly covered most of the present upland areas of the west and north. The emergence of the floor of the Chalk Sea was the last emergence of which we have evidence over the greater part of Britain. Secondly, we have clear evidence that the North Sea Basin is a depression of ancient establishment which has been filling with sediments and subsiding for vast periods. It almost certainly existed during the whole of Tertiary times, and, indeed, gives evidence of its presence much earlier. By comparison, the Irish Sea, St. George's Channel, and the English Channel are comparatively recent features of geological evolution, dating perhaps from the middle or later parts of Tertiary times. In general terms, therefore,

we conceive the original early Tertiary drainage as flowing over a Chalk surface towards the present North Sea Basin or towards the early Tertiary sea of South-east England. An examination of the structural relations of the present drainage systems goes far to justify such a picture (Fig. 113).

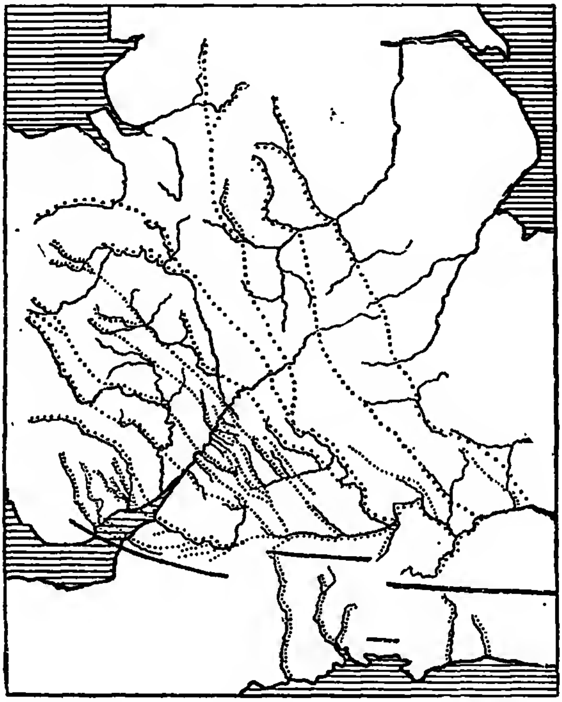
The Kennet-Thames is evidently a longitudinal consequent stream, receiving transverse consequent tributaries (including the Upper Thames) from the north-west, and from the northern flank of the Wealden Dome (Fig. 154). The Dorset Frome represents the head of a similar longitudinal consequent stream draining the Hampshire Basin. This "Solent River" had a similar system of transverse tributaries, but has since been *dismembered* by submergence. Neither the Thames nor the Solent system can have come into being until after the emergence of the early Tertiary deposits over which the rivers flow, but as suggested above (p. 198), they probably did little more than extend the pre-existing drainage system of surrounding lands.[1]

Passing over for the moment the Midland area, we note that the head streams of the great rivers of the eastern Pennine flank from the Tees to the Aire–Humber form an evident series of consequent streams, flowing into the lower Tees and Ouse, which are subsequent in their relations. The former lines of these beheaded consequent streams can be reconstructed in some cases by reference to the drainage plan of East Yorkshire. Thus the Esk, reaching the sea at Whitby, may be regarded as marking the line of the former River Tees. North of the Tees, the Upper Wear and the Tyne fall into place as probable members of the same consequent group, the former having suffered evident diversion by a subsequent stream at the foot of the Magnesian Limestone escarpment. South of the Aire–Humber, the subsequent Lower Trent diverts a number of small consequent streams which, originally, must have continued their courses towards the east.

In the Midland area we are confronted with a much more complex series of relationships which have given rise to more than one interpretation. Subsequent streams, such as the Warwick Avon, the Bedford Ouse, and the

[1] While it is evident that the Solent River flowed eastwards it is unlikely that its ultimate discharge was eastwards into the North Sea Basin, from which it was separated by the Wealden uplift. More probably the drainage turned westwards in the English Channel region.

Upper Thames (west of Oxford), play a large part in the existing drainage plan. One view, adumbrated by W. M. Davis and later adopted to some extent by British writers, represents such subsequent rivers as having broken up a great series of south-easterly flowing consequent streams



[After Buckman.

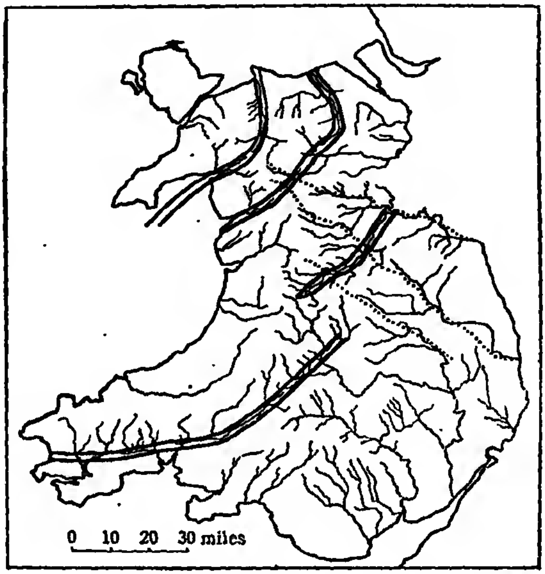
FIG. 155.—A SUGGESTED RECONSTRUCTION OF THE FORMER CONSEQUENT DRAINAGE OF THE MIDLANDS.

Consequent drainage lines=dotted; anticlinal axes=heavy lines.

draining to the Kennet–Thames. An interpretation by Buckman of this theory appears in Fig. 155, which shows not only the Middle Severn and the rivers of South Wales but also certain of the Midland rivers as formerly tributary to the Kennet–Thames, of which, at that time, the Bristol Avon is represented as part.[1] Lake has recently revived

[1] It may be well to remind the reader of what is plainly implicit in foregoing chapters, viz. that all such reconstructions refer to a land-surface far above the lower parts, at least, of the existing land-surface. The conditions shown in Fig. 155, if they existed at all, can have done so only on a surface passing through, or above, the summits of the present higher hills.

interest in this hypothesis by showing that the drainage of Wales shows many features consistent with such a plan (Fig. 156). Radial streams, presumably consequent, are gathered by subsequent streams developed along arcuate zones of fracture or disturbance, as in the case of the Towy Valley or the depression in which Lake Bala lies.



[After Lake.

FIG. 156.—THE DRAINAGE OF WALES.

Former consequent streams, dotted. Fracture-belts along which subsequent streams have developed shown in heavy lines.

The country is thus divided into a series of blocks, each drained from its north-western towards its south-eastern side, and separated from the next block by a narrow subsequent lowland or valley zone. The latter are analogous in relation to the broader subsequent vales of the English Plain, lying athwart the course of the original drainage lines.[1]

[1] It may be noted that the subsequent Vale of Neath takes its place as a minor member of the same series of curving fracture- or shatter-belts, and the Bristol Channel itself may mark a major constituent of the series. If so, the South-western Peninsula of England falls into place as the outermost "block." The plainly marked north-south consequent direction of the Exe, Tamar, etc., accords with this idea.

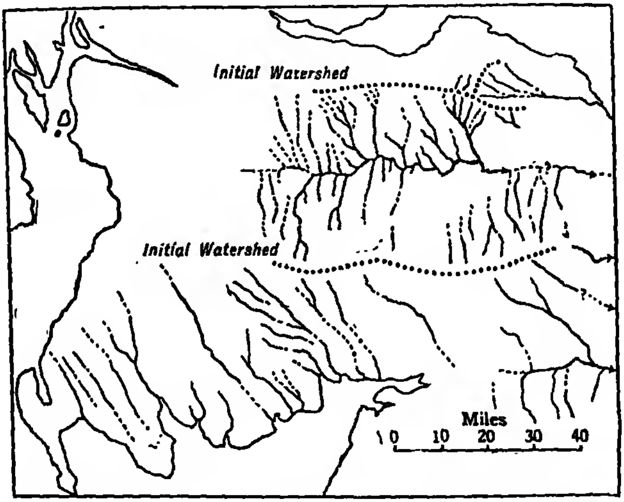
While reconstructions on the lines of Figs. 155 and 156 successfully account for certain features of the Midland drainage, they ignore other significant features which suggest an alternative hypothesis. Thus, there is a striking radiation of the drainage from the vicinity of Rugby. This might be taken as suggesting a dome-like uplift of the initial surface. The Chalk would have rested unconformably on the Jurassic rocks in the Midlands, and hence streams originating as consequents might have been superimposed in longitudinal positions, thus becoming "ready-made subsequent streams." On the whole, this does not seem likely in the case in question, but the possibility is one to be remembered. A variant hypothesis can be based on the fact that the Upper Severn, Penk, Tame, Soar, and Welland flow *northwards*, and might have originated on the northern flanks of an east–west uplift, which threw off similar streams southwards to the Kennet–Thames. The northward flowing streams might be regarded as tributaries of a vanished east to west longitudinal consequent stream, which received also the Upper Trent, Dove, and Derwent as southward flowing tributaries, and passed eastwards to the neighbourhood of the Wash. This hypothesis has the merit of bringing the Midland drainage into line with that of the country to the north and south; and thus serves to give further emphasis to the conception of a series of consequent rivers draining towards the North Sea depression.

Somewhat similar problems arise in the case of the Scottish drainage systems. These have been interpreted by several writers as developed from south-easterly flowing consequent streams, dissevered by powerful subsequent streams picking out the north-east to south-west grain of the country. Linton, however, has shown reason to regard the Tweed as the representative of a former major east–west consequent river (Fig. 157), and the Forth, Earn, Dee, Don, etc., might be regarded as members of the same series, continuing northwards the family of east–west consequent streams represented in Northern England.

We see, therefore, that there are two or more conceivable patterns which we might attribute to the original consequent drainage of Great Britain. The difficulties of reconstruction reflect the long and thorough adjustment to structure which has taken place. To the modifications

so produced we must add those due to glaciation (p. 390), though these are, in general, readily recognized.

A more fundamental problem, on which little light can at present be thrown, is that of the character and date of the movements which defined the western coastline of Britain, and thus brought into being its main watershed and a series of powerful westward flowing rivers, which, by virtue of their steep descent, have performed active headward erosion at the expense of eastward flowing neighbours. These difficulties, however, do not prevent us from reaching certain tentative conclusions concerning the denudation chronology of at least some parts of the system.

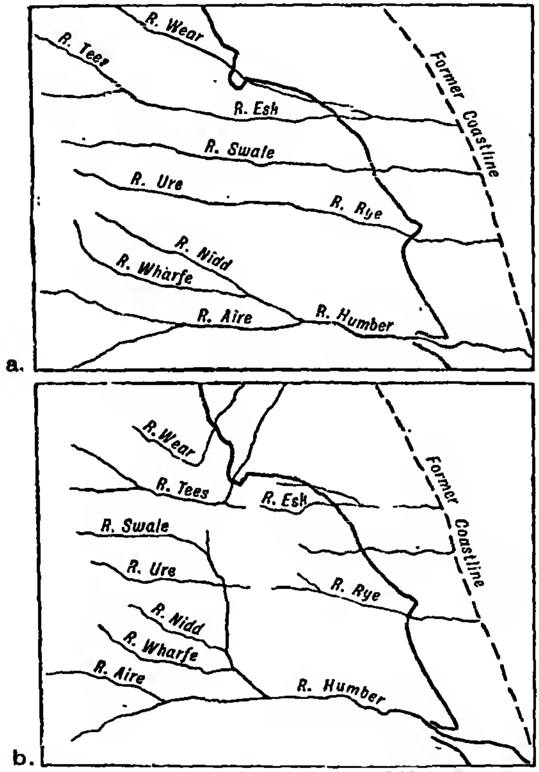


[After Linton.

FIG. 157.—THE CONSEQUENT ELEMENTS IN THE DRAINAGE OF SOUTHERN SCOTLAND.

In Yorkshire, Cowper Reed concluded that the drainage, initiated on a Chalk cover, passed through a complete cycle of erosion, culminating in a peneplain, before the uplift which initiated the current major cycle. The stages of adjustment of the drainage are illustrated in Fig. 158. He regarded the first-cycle peneplain as having been developed well below the Cretaceous base over the greater part of the region, and identified the hill-top plane of the Pennines and its presumed continuation in the hills of East Yorks as the peneplain surface, uplifted with local warping. He assigned a mid-Tertiary (Miocene) date to the uplift. There is no local evidence bearing on

the latter point, and the only reason for the assumption of a Miocene uplift appears to have been the existence of Miocene folding in the South of England. We have seen, however, that regional peneplanation followed the Miocene folding in that area, and so considerable an episode, requiring a long period of time, could hardly be unrepresented by some recognizable feature in Yorkshire.



[*After Cowper Reed.*

FIG. 158.—STAGES IN THE DEVELOPMENT OF THE YORKSHIRE DRAINAGE. (*a*) Initial drainage. (*b*) Drainage in second cycle.

It seems probable, therefore, that the hill-top surface in East Yorkshire is equivalent to the Wealden hill-top plane, and, like the latter, was produced during Miocene times and uplifted in later Pliocene times. Whether one or more complete cycles preceded the formation of the hill-top peneplain in Yorkshire it is, at present, impossible to say The movements associated with the emergence of the

Eocene deposits in the south may have been either strongly or feebly represented in the north, initiating a new cycle of which the record is completely lost, or merely interrupting a long cycle, initiated by the post-Cretaceous emergence.

A broadly similar problem arises in the case of the Welsh drainage in its relations to that of the Midlands, etc. It has sometimes been suggested that the Welsh hill-top plane is the Cretaceous base stripped of its cover, but this can hardly be so. All the arguments used by Johnson in the case of the Schooley peneplain are applicable in some measure here. In the first place, it is most unlikely on *a priori* grounds that a Cretaceous or pre-Cretaceous surface should be so extensively preserved. Secondly, if the drainage had been superimposed directly on the present hill-top surface its consequent lines ought to be more plainly engraved than they are, with all adjustments below the present hill-top; but this is not the case. Thirdly, applying the same argument in different fashion, the general *degree* of adjustment to structure in Wales appears to the writers to point to a previous cycle of adjustment.[1] In the light of present knowledge it seems most reasonable to identify the hill-top plane in Wales, as in Yorkshire, with the late Miocene Wealden hill-top plane, for no younger feature of the Welsh landscape appears to offer itself for correlation with this very important surface.

The foregoing brief survey has left many important areas of British drainage unexplored, and many problems with at best vague and tentative solutions. It is, indeed, intended to convey no final or assured results in a field which still leaves much room both for detailed research and for speculation. It may serve, however, to indicate the types of investigation and argument to be employed in solving this and similar problems.

It should be clearly understood that a full synthesis of British drainage history, when it comes to be made, must embrace much more than the study of "patterns on the map." Such patterns may suggest much, but they can prove nothing. Their indications must be combined with all the evidence bearing on the later geological history of the

[1] An element of personal judgment enters into the last conclusion; it cannot be fully supported or disproved pending the detailed re-mapping of the geology of much of Wales.

area, before sound and tested conclusions can emerge. It is, at least, certain that the evolution of the drainage of the British Isles has occupied not one but several cycles of erosion. Though Tertiary time represents a duration of 60 million years, more than half the period once confidently assigned as the "age of the earth," there is a persistent tendency to underrate the geological work performed during this vast interval. To prevent that foreshortening of the time background, to which geologist and geomorphologist are continually liable, it is necessary to begin work on denudation chronology in areas where tracts of Tertiary rocks survive to give scale and perspective.

CHAPTER XVII

THE GEOMETRICAL NATURE OF RELIEF FORMS AND THEIR REPRESENTATION ON MAPS

THE form of the land-surface is perhaps the most fundamental of all geographical factors, and the problem of adequately representing relief on maps is hence of prime interest to both geomorphologist and geographer. In the foregoing paragraphs we have treated of the *origin* of relief under conditions of normal erosion. It is sometimes claimed that this genetic aspect of the study of relief is primarily of geological rather than geographical interest, and that the geographer can rest content with accepting relief features as they are, treating merely of their influence, direct or indirect, on the life of man. This attitude is at best open to severe criticism; our present purpose, however, is not to pursue so controversial a theme, but to point out that by study of origins we are led to the most accurate conception of the *nature* of relief forms, and thereby equipped to approach the immediately practical problems of representing and "using" relief in the geographical synthesis.

The facets of relief in a landscape of multi-cycle character.—The foregoing discussion has shown that most landscapes are of "multi-cycle" character, peneplanation having been accomplished wholly or in part several times. An analysis of the relief of most areas reveals *surfaces* of different ages with widely differing angles of inclination. For practical purposes we may group the more gently inclined as "flats" and the more steeply inclined as "slopes," leaving the precise distinction between them dependent upon the nature of the area concerned and the purpose for which the distinction is made. From the genetic point of view, both flats and slopes may be subdivided according as to whether they are erosion-surfaces, cut across the structure, or the surfaces of sedimentary accumulations, such as flood-plains, alluvial cones, screefans, etc. Of the two, the flats are commonly the more fundamental, corresponding either to prolonged periods of peneplanation or aggradation, each of which marks a datable phase in the dissection of the country. The

intervening stages of down-cutting are represented by the linking slopes.

We may put the matter in another way by saying that most areas comprise a gigantic stairway of dissected plateaux, each formed at the partial expense of its predecessors, and leading by stages from the existing valley-bottoms to the highest hill-tops ; in imagination we may sometimes carry the " stairway " even higher.

It is in terms of these " flats " and " slopes " that the most reliable and geographically significant account of relief can be given. In the great plain tracts of the world, below 1,000 feet, elevation above sea-level is often the least important of relief considerations. It is shape, not elevation, that counts. In the ultimate analysis, indeed, it is the variously inclined facets of intersecting surfaces which must form the units of detailed geographical study. It is, of course, universally recognized that slope is a determinant of climatic exposure, and a factor in controlling soil-creep, direction of communications, building construction, etc. These obvious controls, however, are effective only on relatively steep slopes. The significance of facets of " flat " and " slope " goes far deeper than this. Each differs from its neighbour in intrinsic qualities, because it has had a different origin. It commonly possesses some unity of soil character, either directly because of geological constitution or because it has been exposed for a longer or shorter time to weathering. The latter consideration applies particularly to flats ; on steeper slopes, downhill drift and wash tend to mask simple differences in soil.

A particularly good example of large scale facets of contrasted type occurs on the Chalk of East Kent. Here the northern part of the outcrop consists of a fairly steeply inclined surface from which the Tertiary beds have been stripped by erosion ; it is only slightly dissected and retains a readily cultivable soil—a relic of the Tertiary covering ; it is a highly farmed country with valley settlements. Farther south is the second facet, inclined at a lower angle and representing a part of the hill-top plane of the Weald (p. 244). This plateau-surface is covered with cold and intractable Clay-with-Flints, still largely wooded. There is little cultivation, and the dissection is here on a much bolder plan, tending to ridgeway roads and plateau settlements. Both of these major facets, of course, include

numerous minor surfaces worthy of distinction in local study.

It is important to notice that contoured maps commonly fail to depict " facets " of surface at all accurately or completely. In mountain regions, where slopes are steep and flats are few, the contoured map does, indeed, present a close approximation to the truth, but at lower elevations it generally fails. For small regions, a good result would be obtained if contours were specially selected to bring out the edges of flats, but this would involve unequal contour intervals. Further, since all major erosion and deposition surfaces slope towards the sea or some inland basin, different sets of contours are required for contiguous areas. This, indeed, is the most vital defect of the contouring method in the present connection. It is perfectly possible to have one gently inclined surface, whose characters make it a veritable geographical unit, but which over a distance of, say, 100 miles, differs in elevation by several hundred feet. It is worth remembering that an inclination of 1° means a slope of over 90 feet per mile. If the range of height becomes too great, climatic and vegetation differences will render geographical subdivision necessary, but at low elevations there are innumerable examples of significant surfaces whose existence is obscured by the contour map. Close contouring, or the use of interpolated form-lines, does not really solve the difficulty, for these devices render it difficult to superimpose other geographical distributions on the map. Hachuring meets the difficulty in part, but does not afford a means of distinguishing between gently inclined slopes of differing character and origin. The desirable ideal is the depicting of distinct surfaces or physiographic units, and for this some form of shading, stippling or tinting would seem to be necessary. No such method could supersede the contoured map ; it would be designed to supplement it for geographical purposes, and such work needs in all cases to be carried out *on the ground.*

Since the contoured map, while an indispensable aid to the geomorphologist, is incomplete in its indications, we may consider certain methods by which its testimony can be supplemented, rendered clearer, or translated into other terms. Such methods are, of course, no substitute for work in the field. They may, however, usefully precede such work and can also assist in portraying its results.

Generalized contours.—When it is required to study the major physiographic facets of an area, it is well to dispense with the complicating details produced by minor valley dissection. For this purpose generalized contours may be drawn, so as to bring out the form of the local summit-planes. Fig. 159 shows such contours drawn to demonstrate the general form of the Chiltern dip-slope. They are carried across the valleys so as to link up points

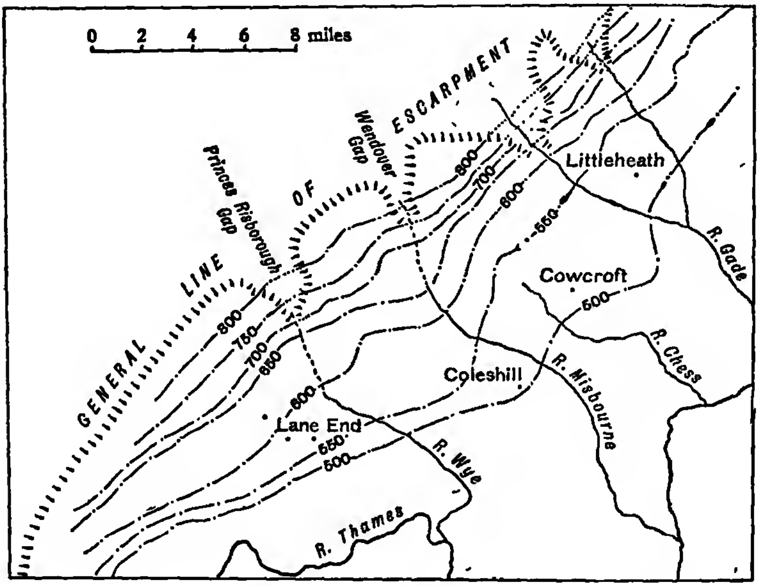


FIG. 159.—GENERALIZED CONTOURS FOR THE CHILTERN DIP-SLOPE.

of equal elevation on the interfluves. It is seen that a broad flat, or bench, occupies the middle levels of the dip-slope at an elevation between 500 and 650 feet; north-west of this flat the general gradient steepens towards the scarp-crest, defining another distinct facet.[1] South-east of the 500-foot contour, a similar steepening (not shown on the map) is traceable in many places.

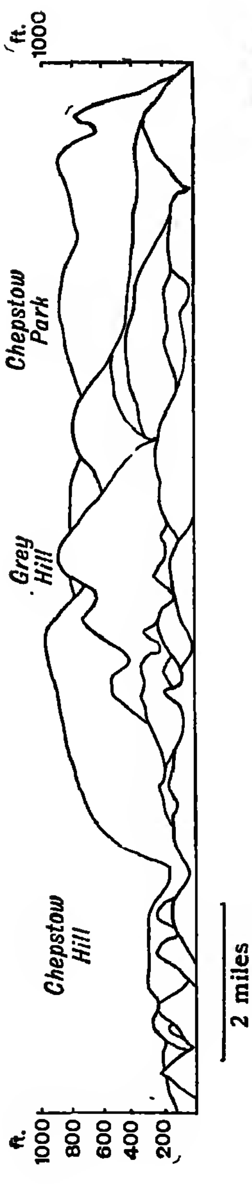
It is evident that this method can only be successfully used where the interfluves are broad and essentially flat-

[1] The features thus brought out prove, on investigation, to be related to the brief trespass of the Pliocene sea in South-east England (p. 247). The bench at 500 to 650 feet is a marine abrasion platform on which relics of Pliocene deposits still survive; the steeper slope behind it marks the coastline of the time, for its southern edge, at least, must represent a degraded line of cliffs.

topped. If maturity has been reached, with sharp-crested ridges, the summit elevations of the latter will have been lowered proportionately to valley deepening. Isolated interfluves thus lowered should be ignored in the reconstruction.

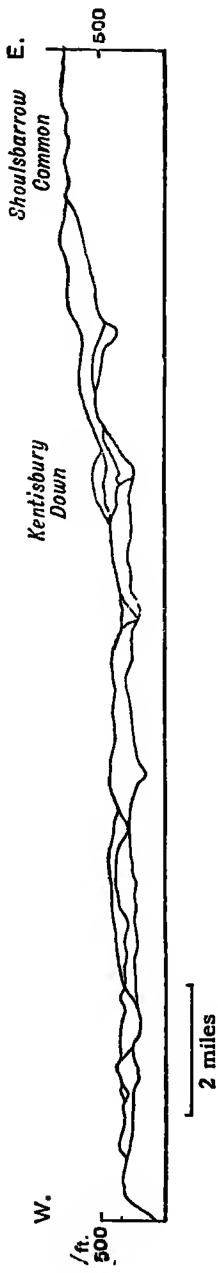
Composite and projected profiles.—Similar information can be obtained by superimposing profile sections, drawn along closely spaced parallel lines. By selecting for emphasis the higher parts only of such a series of profiles, we may construct a composite profile, analogous to a panorama skyline. In general, it is better to present the result in the form of projected profiles, on which less elevated features are included, where not obscured by higher standing areas. A " foreground " is thus preserved for reference, and significant valley-forms, as well as summit-forms, appear in the drawing (Fig. 160). In order to render the method effective, the belt of ground to be projected must be selected judiciously. The work can be done from the map by " projecting " the visible portions of the several parallel sections on to a strip of section paper, with the aid of a T-square. In general practice the sections must be at regular intervals, but if this is done, apparent accordance of hill-top will in some cases be illusory, for if the section line crosses the middle slopes of a spur-termination, a " false summit " will appear. If the lie of the ground is thoroughly known and the problem to be investigated is clearly envisaged, it is legitimate to place the parallel section lines in selected positions, running on or parallel with major ridge-crests. The projected belt will generally be placed transverse to the general slope of the country, but the frontal view of high ground from an adjoining lowland affords a revealing study in some cases (cf. Fig. 160*a*).

Hypsographic curves.—Hypsographic curves, in which elevation is plotted against areas, can be used in detailed morphometric work, just as in the generalized representation of the major features of terrestrial relief (p. 38). The ideal curve for an area which had suffered uninterrupted denudation by water-erosion, after a single simple uplift, would be of regular form, concave upwards, representing, as it were, the generalized curve of water-erosion. The preservation of portions of planation surfaces or " platforms " must modify the curve, by superimposing a convexity on its simple concave form, at points corresponding with the general heights of the several " platforms." Fig. 161



[After Miller.

FIG. 160 (a).—PROJECTED PROFILE LOOKING NORTHWARDS, NEAR CHEPSTOW, MONMOUTH.



[S. W. W.

FIG. 160 (b).—PROJECTED PROFILE IN THE COUNTRY SOUTH OF ILFRACOMBE.

shows hypsographic curves, drawn for the areas included on certain sheets of the Ordnance Survey of England and Wales (½ inch to 1 mile). A slight convexity is apparent on one curve at about 500 feet, and all show evidence of planation at about the 200-foot level. Both the features thus indicated are amply demonstrated on the ground.

The data for construction of hypsographic curves are obtained by measuring the areas between each pair of contours in turn, and expressing each area as a percentage of the total area. The measurement can be carried out

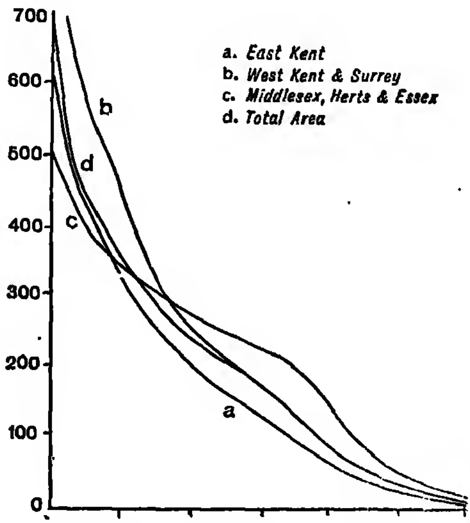


FIG. 161.—HYPSOGRAPHIC CURVES FOR THE COUNTRY AROUND LONDON.

The areas represented by the curves a, b and c are respectively those shown on the sheets 40, 34 and 29 and 30 of the Ordnance Survey ½-inch map.

with a planimeter; or, in the absence of this instrument, by obtaining the aggregate intercepts between each pair of contours along a series of closely spaced parallel lines covering the whole of the sheet. Such aggregate intercepts are proportional to the area.

Clinographic curves.—The hypsographic curve shows the variation in the extent of successive altimetric zones. When used as above it is intended to bring out major variations in the average slope of the area. It will, in fact, bring to light such major variations in most cases, but it must fail to reveal slight, but significant, changes of

slope, and it may also indicate apparent breaks of slope where none in fact occur. Thus, in country where a few hill-tops just exceeded a height of 1,000 feet, but broad gentle slopes continued to the 900-foot contour, the hypsographic data would reveal a large difference in the areas above 900 and 1,000 feet respectively. On the curve, this would appear to indicate a marked flattening of the slope between 900 and 1,000 feet, which, in fact, would not occur.

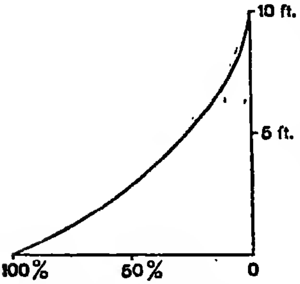
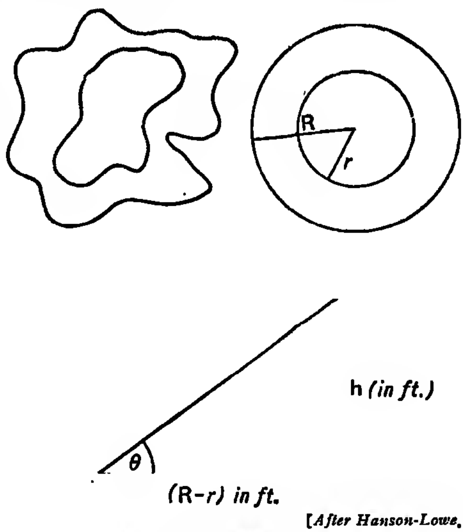


FIG. 162.—HYPSOGRAPHIC CURVE FOR A CONE TEN FEET HIGH.

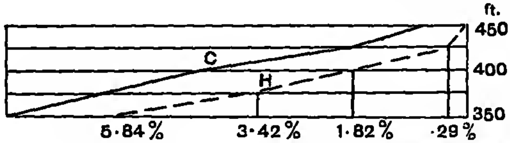
Hanson-Lowe has called attention to this evident limitation of the hypsographic curve in morphometric work, noting also that the curve for a right-cone is not a straight line, as might be supposed at first sight, but a curve concave upward (Fig. 162). He has, therefore, proposed the use of a *clinographic curve* designed to show the actual variation of average slope in an area. The data required are the same as for the hypsographic curve. If x and y are the areas enclosed by two successive contours of irregular form (Fig. 163), we can imagine them replaced by two concentric circles of radii R and r respectively, such that: $x=\pi R^2$ and $y=\pi r^2$. If $R-r$ be expressed in feet, in accordance with the scale of the map, and the contour interval be h feet, the average angle of slope (θ) between the contours can be obtained, since $\tan \theta=\frac{h}{R-r}$. The curve can be constructed by drawing the



[*After Hanson-Lowe.*

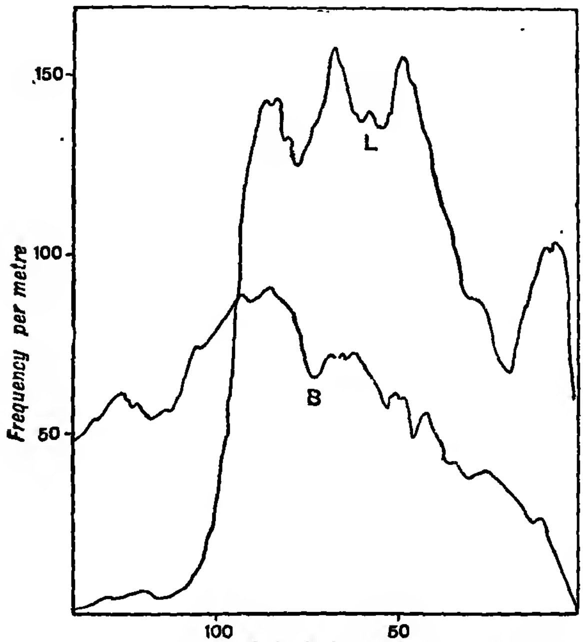
FIG. 163.—MODE OF CONSTRUCTION OF CLINOGRAPHIC CURVE.

average slope between successive pairs of contours with a protractor (or by using a table of co-tangents). Since very gentle slopes will increase the length of a clinographic



[*After Hanson-Lowe.*

FIG. 164.—CLINOGRAPHIC (C) AND HYPSOGRAPHIC (H) CURVES FOR THE ISLAND OF JERSEY.



[*After Baulig.*

FIG. 165.—ALTIMETRIC FREQUENCY CURVES FOR PENINSULAR BRITTANY (B) AND LEON (L).

diagram inconveniently, it is best to multiply each gradient in degrees by some factor, thus exaggerating the vertical scale, but preserving the relative values of the slopes unchanged. Fig. 164 compares the hypsographic and clinographic curves for the island of Jersey as constructed

by Hanson-Lowe. The considerable differences between them and the evident advantages of the latter for morphometric work may readily be noted.

Altimetric frequency curves.—Another method of morphological analysis, applied with some success in France, involves the frequency of occurrence of "spot heights" on high or culminating points. If the map is divided into small uniform squares, we may estimate the elevation of the highest point in each square, or use simply the spot heights shown on the map, providing that these, in general, mark elevated points. A curve may then be constructed showing altitudinal distribution of such points over the region. Well-marked maxima on the curve indicate the presence of fairly level benches or platforms, though subsidiary maxima may arise by coincidence. Examples of such curves constructed by Baulig are shown in Fig. 165. The method, though laborious, is more rapid than full planimetric measurement, though the results are distinctly less definite and accurate. It should be noted, further, that the location of spot heights on British maps does not on the whole favour the method. It is perhaps best adapted to rapid investigation on maps of relatively small scale.

CHAPTER XVIII

UNDERGROUND WATER

In dealing with the erosive work of rivers we made no inquiry as to the relation between the surface-flow and the underground movement of water, accepting without preamble the evident fact that, in regions of normal erosion, part of the rainfall is discharged over the surface. We must now examine the principles governing the accumulation and movement of underground water, since apart from their practical importance, the processes involved share notably in the shaping of the surface of the earth.

The disposal of rainfall.—Granted the existence of an accurate rainfall map, it is a simple matter to determine the total volume of rain falling annually on a given river basin. Dividing this total by the area of the basin, we obtain a figure known as the pluviometric index (P), representing the depth of the annual rainfall, regarded as spread out in a uniform layer. If the average annual discharge of the river is similarly divided by the area of the basin, we obtain the index of discharge or run-off (D). It follows that:

P — D = (water lost by evaporation) + (water lost by percolation) — (water returned to surface flow through springs)

The ratio $\frac{D}{P}$, known as the coefficient of discharge evidently depends on a number of variable factors, climatic and geological. Figures expressing the ratio of run-off to rainfall for certain European rivers are as follows:

Elbe (Bohemia)	28 per cent.
Inn (at Innsbruck)	80 per cent.
Rivers of Great Britain	25–35 per cent.
Seine	33 per cent.

The importance of geological conditions in relation to discharge is illustrated by the following comparative figures for the Thames and the Severn Basins above Kingston and Gloucester respectively.

River	Area of Basin	Mean Rainfall	Summer Discharge[1]	
			Mean	Minimum
Thames	3,670 sq. miles	27 inches	688	350
Severn	3,890 sq. miles	40 inches	298	100

[1] In millions of gallons per day.

It thus appears that the Thames, with a lower mean rainfall and a smaller basin, maintains a larger discharge than the Severn. This is due to the fact that its flow is maintained to a considerable extent by water stored underground in rocks, such as the Chalk, and returned to the surface through springs. The Severn has no such capitalized reserve of water, the run-off of the district being in general more immediate and therefore more spasmodic.

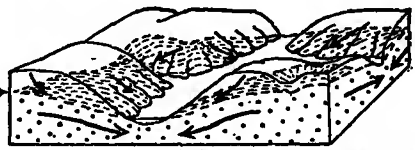
It is evident from the above example that underground water must play a large part in conditioning surface-erosion, apart altogether from its direct work beneath the surface. If underground storage were impossible, surface-forms would certainly be very different. Actually there exists everywhere below the surface an accumulation of "ground-water," though it varies greatly in amount from place to place. It is chiefly of direct atmospheric provenance, representing the percolation quota of the above equation.[1]

The water-table, wells, and springs.—Rocks in their relation to underground water fall into two main classes, according as they are pervious or impervious. *Perviousness* as a rock character must be clearly distinguished from *porosity*. Crystalline rocks show but the slightest porosity, since their crystals interlock, but they may be highly pervious in virtue of numerous joints. Conversely most argillaceous rocks, while distinctly porous, are essentially impervious. The pore spaces are too small to allow free passage of water, which is firmly held by surface tension. Rocks which will hold and permit the passage of water are called aquifers.

In a large number of cases, a pervious rock occupying the

[1] It must be supplemented locally by such other sources as: (*a*) "intra-telluric" or juvenile water, set free in the crystallization of igneous rocks; (*b*) original water of sedimentation, remaining in sediments from the time of their formation; and (*c*) ocean water which percolates inland. The "wandering" or "vadose" water above the water-table varies greatly in amount and position.

surface is underlain by some impervious stratum, and the downward percolation of water is thereby checked. In any case, however, there is a general lower limit set to downward percolation, by the increase of rock pressure with depth, which ultimately closes all open passages through the rock. Above the downward limit of percolation, however caused, there will be a thickness of rock, saturated with water in respect of all pore spaces and other cavities. Locally, the saturation may extend to the ground surface, but, in general, its upper limit is below the ground, and is referred to as the *saturation level* or *water-table*. Wells dug to sufficient depth will fill with water to this saturation level.



[*After Longwell, Knopf and Flint.*

FIG. 166.—THE RELATION OF THE WATER-TABLE TO THE LAND SURFACE
Directions of water movement shown by arrows.

If a pervious rock were homogeneous in respect of pore-spaces and divisional planes, and if supply by percolation were everywhere equal, the water-table would justify its rather misleading name and assume a horizontal position. Actual water-tables are, in fact, much more complex in form. Inequalities of rainfall or percolation result in the piling up of water beneath certain areas. In such cases a lateral flow at once begins, carrying water from areas of high to those of low water-table. Variations in perviousness make themselves felt, so that lateral flow proceeds more readily in some directions than in others.[1] As a result, the water-table becomes complex and irregular in form. Moreover, where the water-table intersects the surface in valleys and depressions, further systematic variations of level arise, which roughly reflect the form of the land-surface. This common condition is pictured in Fig. 166, where springs are shown on the valley-sides, at

[1] The perviousness of a water-bearing rock, such as the Chalk, has been shown to vary with the " load " of overlying rocks. Heavily loaded areas where the Tertiary cover is thick, afford poor yield in wells, probably owing to the closing of joints and fissures by the weight of the overburden. Again, anticlinal areas tend to show open joints, while in synclinal areas the joints are closed. Within the London Basin the heavily loaded areas are generally synclinal in structure (Fig. 169), and the two effects no doubt co-operate in reducing perviousness.

the points where the water-table emerges, the valley-bottoms being occupied by flowing streams. In such cases the water-table is lowered in the vicinity of the valleys to an extent proportional to the volume of spring flow. The valleyward water-table slopes represent hydraulic gradients, necessary to overcome the frictional resistance to the passage of the water, which maintains the discharge of the springs.

The principle noted above in connection with the discharge of springs is of general importance, and we may illustrate it more simply by reference to the common case of an outlier of pervious material resting on an impervious stratum. In such a case, springs mark the lower edge of the pervious cap. The common elementary explanation offered is that percolating water reaches the surface of the

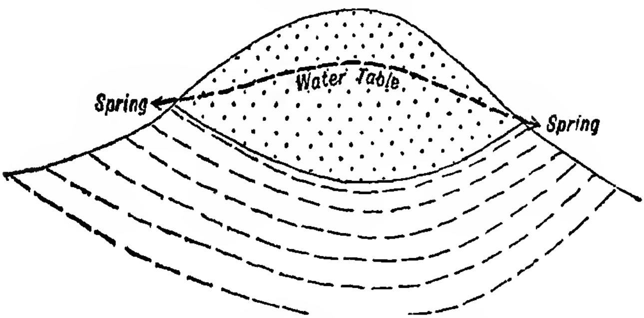


FIG. 167.—SYNCLINAL OUTLIER WITH SPRINGS.

lower stratum and runs along its surface to the points of outflow. The explanation is erroneous or represents, at best, a rare and local phenomenon. It assumes that the form of the surface of the impervious bed permits of an outward flow; even if it did, the frictional resistance to the passage of small quantities of water would be, in general, so great as to prevent outflow, or to permit only a very slow and insignificant seepage. In fact, many water-bearing outliers owe their very existence to a slight synclinal structure (Fig. 167), and even if the sub-surface basin be filled with water no appreciable outflow can result. The actual conditions are represented in Fig. 167, where the water-table stands high beneath the hill-crest and descends at an angle sufficient to maintain outflow; in short, to give rise to the spring there must be a head of water.

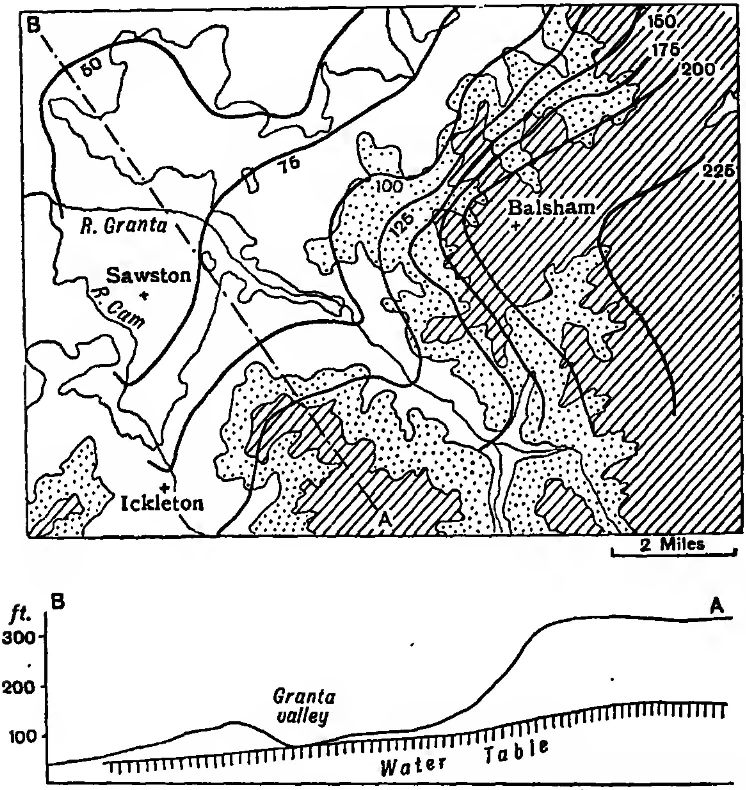
We are thus led to conceive the water-table in a single pervious stratum as an undulating surface, owing its irregularities to inequalities of supply, internal transit, and discharge, and down the slopes of which water moves. In respect of percolating water from above, the water-table evidently behaves like the surface of an impervious stratum. Further, it must clearly rise and fall with the rainfall seasons, though since percolation is in general slow, its fluctuations will lag markedly behind the corresponding maxima and minima of rainfall.

Some confusion is apt to arise concerning the relation of surface-streams to the water-table. In an area of highly impervious rocks of great thickness, there is, of course, no regional water-table near the surface, though water may be stored far below ground, out of reach of the deepest valleys (p. 274). In such a case the run-off of the streams accounts for nearly all the rainfall not lost by evaporation. Nevertheless, there are no areas in which small amounts of percolation do not take place, down chance cracks and crevices. This lends to a limited accumulation of water in "pockets." Moreover, streams traversing a generally impervious terrain will be related to a water-table in their own alluvia, if these are of pervious type.

In areas of pervious rocks it is frequently only the larger valleys which intersect the dry season water-table. If we take as an example a sandstone upland, it is clear that the wet weather runnels which form the heads of the valley system are far above the main or permanent water-table. In spite of this the rock is not able to absorb water fast enough to take up the whole of the surface flow. Such streams are liable to loss by leakage on their way to the main valleys, but a considerable body of water may survive as surface-flow, particularly if slopes are steep and the time available for percolation therefore short. In some cases even a large stream may survive for long periods the disappearance of the water-table below the valley-floor, in virtue of its own muddy alluvial deposits. These effectively "puddle" the lower river course, and thus enable the discharge of upstream areas to be carried across a tract of absorbent rocks.

It will be seen from the foregoing paragraphs that the basic principles governing the accumulation and movement of underground water are relatively few and simple. The complexities of the subject arise through the wide variety of geological structures and our frequent ignorance of the

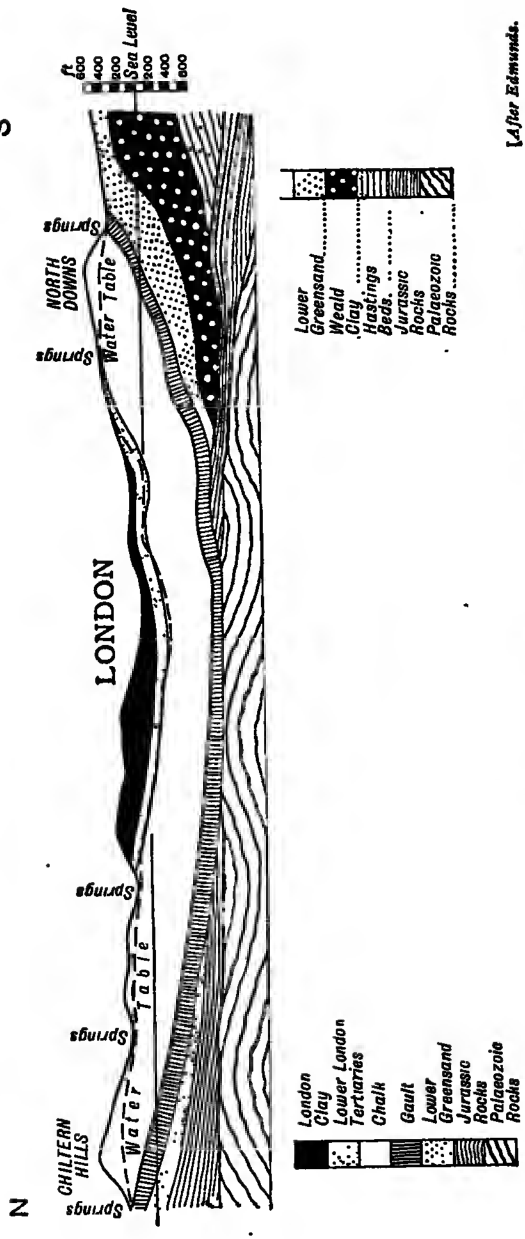
detail of these structures. We have spoken above of a single water-table, subject to seasonal movements, established in a pervious rock-mass of considerable thickness. In general, however, an area will show duplicated or multiple water-tables. For the accumulation of sub-surface water a complete impediment to downward per-



[*After H.M. Geol. Survey.*

FIG. 168.—THE FORM OF THE WATER-TABLE IN PART OF CAMBRIDGESHIRE. Water-table contours (feet) in heavy lines. Ground above 200 feet=dotted; above 300 feet=shaded.

colation is not necessary. There is a tendency for accumulation to take place above every geological junction at which percolation is to some extent checked by the superposition of a more pervious on a less pervious rock. If gravel rests on fine-grained sandstone, there may be a distinct water-table in both, owing to the fact that the

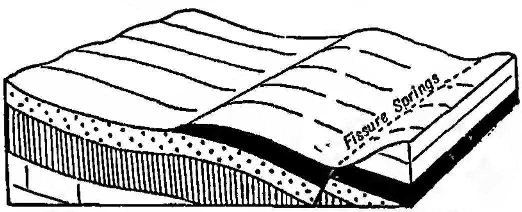


[After Edmunds.

FIG. 169.—THE LONDON BASIN, WITH THE WATER-TABLE IN THE CHALK.

gravel passes water down, faster than the sandstone can take it up. The same phenomenon may occur within the confines of a single, generally pervious, rock-mass of varying porosity or state of fissuring. It is only where wells are especially numerous that it is possible to reconstruct the form even of the main water-table of a district (Fig. 168). Rarely, indeed, is there sufficient information to enable one to picture the many secondary and temporary water-tables, yet their existence is rendered evident by springs, and can be safely inferred from the geological conditions.

When we pass on to consider the many possible associations of definitely pervious and impervious beds, and their very varying attitudes, we are evidently confronted with a host of special cases, of which only a few can here be considered. The most important cases are those in which aquifers are interstratified with impervious strata, and



[*After Longwell, Knopf and Flint.*

FIG. 170.—FISSURE SPRINGS.
The dotted bed is the aquifer.

inclined at an appreciable angle. The aquifers are filled at the expense of rain falling on the outcrop, but travelling down the dip for considerable distances. The water-table descends in the same direction as the geological dip, but in general at a lower angle. If there is an impervious covering rock, the whole thickness of the aquifer may be saturated. With a synclinal structure, this gives rise to a true artesian basin (Fig. 169). Under the impervious cover, the water is prevented from rising to a natural level; but as soon as the cover is pierced the water rises naturally, in wells, to a height depending on the height of the water-table on the flanks of the basin.

We are not here concerned with artificial artesian wells, but we may note that springs (dip-foot springs) are liable to occur on the edge of the impervious cover (Fig. 169) representing water descending the dip for which room cannot be found in the already saturated aquifer. Moreover, faults or other fissures may afford opportunity for the

artesian rise of water from beneath the cap-rock (fissure springs) (Fig. 170). If the aquifer, commonly sandstone or limestone, is a scarp-forming element, we shall also find springs, representing normal leakage, at the base of the escarpment (scarp-foot springs) (Fig. 169). The water-table will fall from a culminating level roughly beneath the scarp-crest, towards both the scarp-foot and the dip-foot springs. These three types of springs are of systematic occurrence in regions of uniclinal or gently folded structure, though fissure springs are not so common as scarp-foot and dip-foot springs. These latter contribute great volumes of water to the subsequent streams, which are so regular a feature in regions of the scarpland type.

CHAPTER XIX

THE GEOMORPHOLOGY OF LIMESTONE REGIONS

Introductory.—We have seen on an earlier page that structure (including rock constitution) is an evident factor in landscape. Nevertheless, in most regions, "stage" and "process" are perhaps of more importance in determining the main outlines of landscape. For instance, areas respectively sculptured in coarse-grained crystalline rocks and sandstone will show in detail undoubted differentiæ due to rock character, but if both are in the same stage of development under normal erosion, the major lineaments of the landscape will be generically similar. So, too, in the higher parts of the Alps the insignia of glacial erosion impose a general unity of form, largely independent of rock character. In general, it is true to say that process and stage decide the genus of most landscapes, while structure determines the species. There is one conspicuous exception to this rule, however. Limestone country,[1] whatever its general attitude or climatic environment, shows unmistakable features which depend primarily on the qualities of limestone as a rock. Its outstanding qualities are its solubility in carbonated waters and its common possession of a well-developed system of jointing; both are chiefly significant in connexion with the behaviour of underground water. The morphology of limestone terrains is closely linked with their hydrology, and we may fitly discuss the matter as a special sequel to the last chapter.

Within the general field of limestone landscapes the chief contrast is between those based on the soft unlithified limestones, such as Chalk, and those developed from the harder limestones, which have undergone self-cementation (p. 136). It should be noted that both types are "soft," judged by the mineralogical criterion of resistance to scratching, *i.e.* both succumb readily to mechanical abrasion. The fact that both types tend to stand up prominently in relief is due to their common propensity for "swallowing" surface drainage. They are

[1] Limestone must here be read as including dolomite.

thus "resistant" to the general processes of landscape degradation, but not "hard."

The compact or crystalline limestones give rise to striking common features of landscape over a wide range of climatic conditions. They are best seen in the "karst" landscapes, but they are not confined to the true karsts. The Chalk landscapes are equally distinctive, though they have not received equal attention. Since, however, they are quite as important to the European, and particularly the British student, we shall make no apology for treating them first. They will be found to afford considerable light on certain features of the much discussed karsts.

The English Chalk country.—The Chalk of England and France is a soft white limestone, containing a small and variable admixture of clay and sand, and showing in its upper part bands and nodules of concretionary flint, formed by the segregation of silica within the mass. Topographically, the Chalk country is of rolling type, but with marked relief. Its rounded profiles were so familiar to "Strata Smith," the great pioneer of stratigraphical geology, that he identified the Chalk of the Yorkshire Wolds from the Tower of York Minster before visiting the area. The main valleys containing perennial streams are widely spaced. Many, but not all, of these streams are "allogenic," deriving much of their water from terrains beyond the Chalk outcrops. The valleys tributary to the main river valleys are nearly all streamless, and between the watered valleys are whole valley systems, main trunk and branching affluents, which are now dry (Fig. 171). The valley-slopes are steep and the bottoms rounded, unless, as is often the case, they form the upper surface of a filling of gravel and hill-wash (Fig. 128c). So numerous are the valleys of the Chalk country that a map of existing water courses conveys a quite inadequate impression of the extent of dissection. Thus in a twenty-five mile traverse along the lower part of the Chiltern dip-slope, from near Marlow to Redbourn (Herts), one would cross five main valleys with flowing streams more or less equally spaced, but between each pair one or more major dry valleys occur. A parallel traverse nearer the Chiltern crest would cross some thirty or forty valleys, for each trunk splits upstream into many branches (Fig. 171). Despite this pronounced dissection the interfluves over wide areas are even-crested or flat-topped (Fig. 128c). Thus, judged by the criterion used in

the normal cycle of erosion, the topography is still youthful or sub-mature.

Where the geological dip is slight, the Chalk country has the form of a dissected plateau. Above some parts of the plateau-surface are conspicuous outliers of Tertiary sands and clays, while larger areas are covered by a mantle of Clay-with-Flints. The latter was at first interpreted as a residual deposit, the insoluble residue of ages of atmospheric solution of the underlying Upper Chalk. For part of the Clay-with-Flints this is no doubt a true explanation, but large quantities of Tertiary debris and masses of wind-blown loess of Pleistocene date are

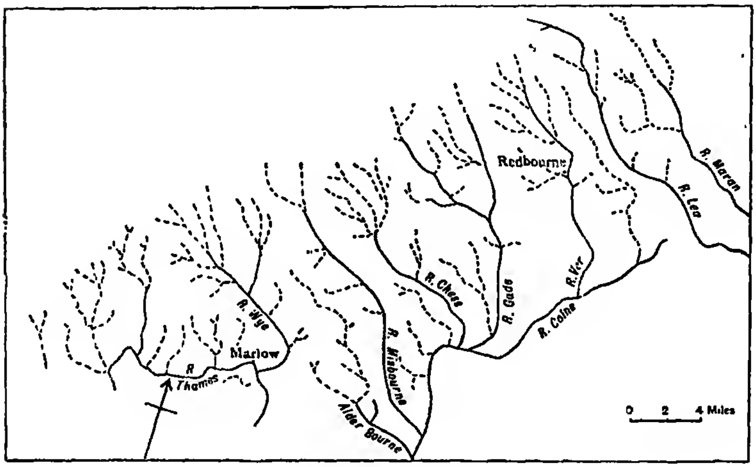


Fig. 171.—The Valleys of the Chiltern Dip-slope.
Dry valleys dotted.

locally mixed with it. The mixture has been regarded by some as of truly glacial origin. For this there is no certain evidence, but the mass certainly shows signs of having moved as a sludge, probably during phases of thaw in Pleistocene times. Though few favour the presence of ice-caps, there must certainly have been snow-caps on the higher parts of the English Chalk country, and in melting they no doubt facilitated solifluction in the surface deposits (p. 402). Where the Chalk cover of the English Plain is breached, its edge stands in a prominent escarpment, of which the base is encumbered by sheets and fans of "coombe-rock," the product of wash over a frozen surface (p. 403).

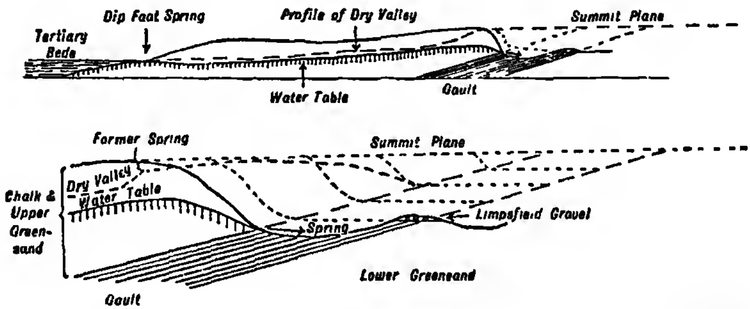
The hydrology of the Chalk.—The Chalk is the principal water-bearing formation in England, and its hydrology has been studied in considerable detail. Normal Chalk is porous, and will hold large quantities of "water of imbibition," which, however, does not drain freely from the mass. Water-movement in the Chalk takes place largely along joints and fissures. Wells and vertical shafts sunk in Chalk frequently remain dry, unless horizontal headings are driven to intersect water-bearing fissures. There is no doubt that such fissures are widened by solution as a result of the activity of descending water. Although large solution caves are rare or absent in Chalk, small caves and gaping fissures have been recorded. At Knockholt (Kent), at a depth of 270 feet, a cavern 30 feet by 12 feet by 30 feet was encountered, while at Rochester an enlarged fissure 12 feet wide and 17 feet high was traced for a distance of 150 feet. The complement of the solution process is seen in the fact that many Chalk springs deposit calc-tufa, and it has been estimated that every square mile of a Chalk district loses 140 tons of matter in solution each year.

The water-table in the Chalk on the flanks of the London and Hampshire Basins is of the general form shown in Fig. 169. In the centre of the London Basin, beneath the covering of London Clay, it formerly stood at the top of the Chalk, or above it in the Tertiary sands. In the London area it has been artificially lowered by the pumping of wells, and is now 100 feet or more below the top of the Chalk in many places.[1] The form of the water-table beneath the Chalk outcrop in Surrey is shown in Fig. 172. The annual rainfall on the crest of the North Downs is 35 inches, 10 inches in excess of the total on the lower ground near Croydon. This assists in maintaining the high standing area of water-table beneath the Downs. From the crest it descends steeply to the base of the escarpment, where powerful scarp-foot springs break out at the junction with the underlying Gault Clay. It declines more gently towards the edge of the Tertiary outcrop. West of Croydon, dip-foot springs emerge to feed the Wandle, but east of Croydon the water-level is well down in the Chalk at the point where the Tertiary beds come on.

Bournes.—The area illustrated in Fig. 172, presents many of the typical phenomena of the English and French

[1] In 1911 the water-level in the wells supplying the fountains in Trafalgar Square had fallen more than 115 feet in sixty-four years. The wells in Kensington Gardens had fallen 90 feet in forty-seven years.

Chalk country, and its hydrology has been very thoroughly studied. Amongst the most interesting features is the "Croydon Bourne," a stream which intermittently occupies the normally dry upper valley of the Wandle, above Croydon. Such intermittent streams characterize all the Chalk areas. They are known as nailbournes in Kent, winterbournes in Wiltshire, lavants in Hampshire, and gypseys in Yorkshire.[1] The normal seasonal fluctuations of the water-table are insufficient to flood most of the dry valleys, but at longer intervals, after exceptionally heavy rains, the bourne flows break out and last for a few months. Fig. 173 illustrates the associated conditions of



[*After* Fagg.

FIG. 172.—HYDROLOGY OF THE CHALK AREA OF SURREY.

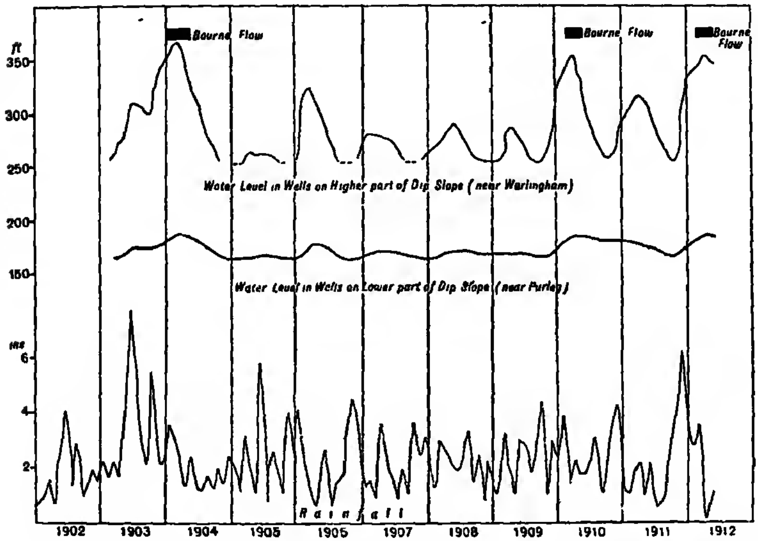
Above, water-table, scarp-foot and dip-foot springs and profile of dry valley. *Below*, the recession of the chalk escarpment with resulting depression of the water-table (p. 286).

rainfall and water-table (in wells) for the three outbreaks of the Croydon Bourne between 1902 and 1912. The Hertfordshire Bourne near Hemel Hempstead made eleven appearances in the half-century 1853-1903. In most cases there is a favoured point of emergence for a bourne-flow—no doubt where a major fissure strikes the valley-floor—but evidently the length of a bourne must be variable according to the amount of rise in the water-table. It commonly extends its head upstream following its first appearance. Several of the Chiltern rivers have a variable "bourne-head" above their normal source.

Swallow holes and "pipes."—Bournes are due to temporary abnormal elevation of the water-table; equally

[1] The outburst of these streams was popularly regarded as a portent of pestilence or other disaster in bygone times. Pestilence did, in fact, accompany them, for when they flowed there was a concurrent rise of contaminated ground water in domestic wells.

striking effects result from intermittent depression. The River Mole, crossing the Chalk between Dorking and Leatherhead in Surrey, behaves for long periods as a normal stream, flowing in a valley where the water-table is at, or slightly above, the surface. At other periods it disappears over a portion of its course, only to reappear farther downstream. At these times the water-table evidently sinks below the valley-floor, and the stream descends to it through conical holes, some feet in diameter, known as swallow-holes (Fig. 174). These form by solu-



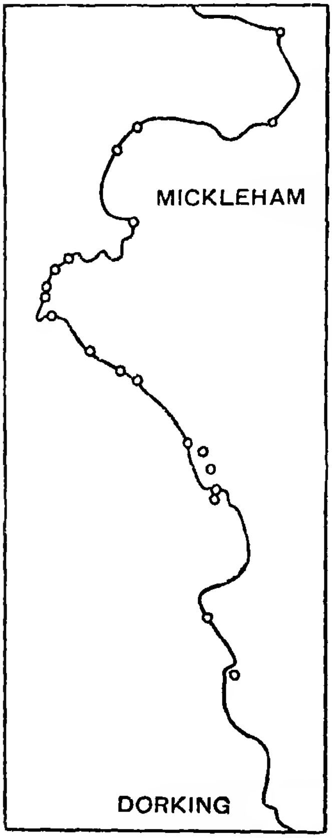
[*After Barrow and Wills.*

FIG. 173.—CONDITIONS OF RAINFALL AND WATER-TABLE ASSOCIATED WITH THE OUTBREAK OF THE CROYDON BOURNE.

Water level given in feet above Ordnance Datum.

tion of the Chalk, probably along lines of intersection of major joints. They may be blocked in their upper portion by surface debris or crumbling of the sides, but they readily admit the downward passage of water. They occur on the floor and the edges of the stream-bed, and scattered over the flood-plain. Similar phenomena leading to much more striking topographic effects occur at North Mimms (Herts), where an obsequent headstream of the River Colne, draining some scores of square miles of clay country to the south, periodically discharges the whole of its water down a group of large swallow-holes

ranging up to 30 feet in diameter and 20 feet deep. The floors are generally cumbered with mud, but when this dries and cracks, glimpses are obtained of the gaping channels which lead the water far below the surface. The swallow-holes, of which some fifty or sixty can be identified, open from the floor of a major depression with characteristic "scalloped" edge (Fig. 175). This has evidently formed by the growth and coalescence of swallow-holes of a previous generation. As a result, a considerable "solution subsidence" has occurred, reminiscent of the so-called "uvalas" of the karst (p. 289). Minor streams draining to the depression record the stages of its subsidence, by clearly marked back-cutting, of which the head is reached a short distance upstream. In winter floods, the whole depression forms a temporary lake, for the inflowing water arrives faster than it can be taken up by the swallow-holes. At such times an overflow channel leads north-westward into the main stream of the Colne, and surface drainage is temporarily continuous.[1]



[*After H M. Geol Survey*

FIG 174.—SWALLOW-HOLES ALONG THE RIVER MOLE, SURREY

Conspicuous swallow-holes along water courses are comparatively rare, since they tend

[1] This is one of the very few cases of major solution subsidence known in the English Chalk lands A possible example, on an even larger scale, occurs near Lane End, Bucks, where a strip of country, floored by Tertiary deposits, 1 000 feet wide and some two thirds of a mile long is depressed below its true level, so as to imitate a miniature rift valley It has been regarded as bounded by faults but the nature and cause of the faulting are not clear It is possible, though not proved, that the subsidence was due to solution in the underlying chalk Large swallow holes occur near the edges of the sunken block The area seems to be comparable in some respects with the smaller poljes of the karst (p 289)

to be filled and obliterated, but at higher levels, far above the saturation plane, they are very common in Chalk country. The common situation is near the edge of impervious cap rocks, such as Tertiary outliers or spreads of Clay-with-Flints. Water flowing over the surface of such beds sinks into swallow-holes when it reaches the underlying Chalk The swallow-holes thus appear as aligned dimples in the surface, many of them silted up and no longer functioning. But, as Darwin noted, swallow-holes form in all situations over the higher parts of the Chalk country, and they are to be regarded as the natural water conduits for down-

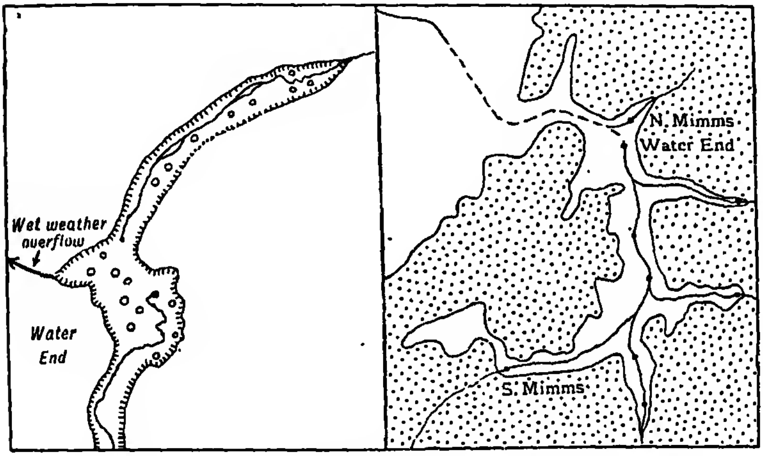


FIG. 175.—DISAPPEARANCE UNDERGROUND OF MIMMSHALL BROOK, S. HERTS.

Right, Tertiary rocks are dotted; chalk=white; swallow-holes=large dots; wet weather overflow course=dashed line. *Left*, an enlarged sketch of the sunken area, pitted with swallow-holes at Water-End.

ward percolation above the water-table. They can form beneath a shallow cover of pervious sand or gravel, which subsides into the depression as it grows. Thus are formed the familiar " pipes " seen in section in many chalk pits (Fig. 176); in reality the " pipes " are " fossil " swallow-holes.

Though the number of swallow-holes in Chalk country is large in the aggregate, they are rarely grouped so as to affect the form of the surface in any conspicuous way. In this respect Chalk country differs from the karsts.

The dry valleys of the Chalk.—With the chief physical features of the Chalk terrains now before us we may briefly

examine the major physiographic problem they present, viz. the origin of the dry valleys. The form of the valleys leaves little doubt that they were eroded by flowing water, though solution, as well as abrasion, must have played a large part. Moreover, they form as a whole, systems mutally accordant, and the dry tributaries of the watered valleys show similar accordant relations. Sometimes the branches of a system hang slightly above the trunk valleys, whether wet or dry. This is well seen in the tributary coombes of the River Cuckmere near Alfriston (Sussex). But in all cases the discordance is so slight as to prove clearly that the excavating conditions have not been long in abeyance. A comparatively small rise of the water-table would suffice to provide the larger valleys with streams, as is evident from the bourne phenomena. A much larger rise would be necessary in the case of the branching head valleys of the system. At first sight the simplest means of explaining such a rise would seem to be

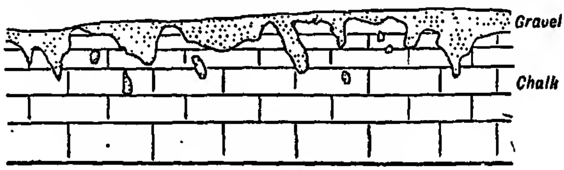
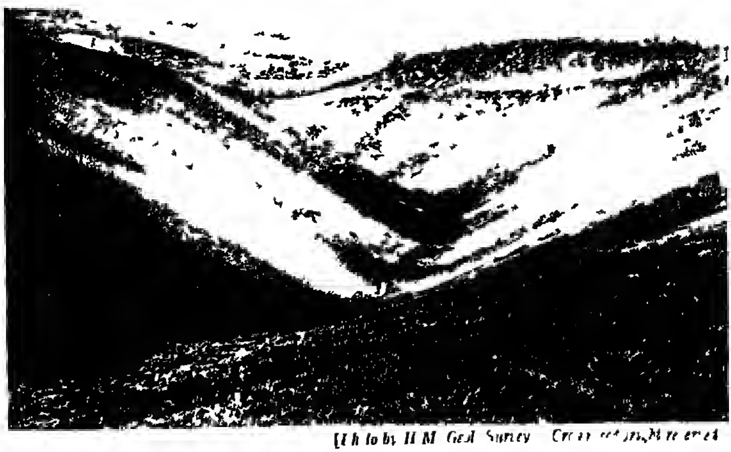


FIG. 176.—GRAVEL-FILLED PIPES IN CHALK.

the assumption of a formerly higher rainfall. But this is an entirely *ad hoc* assumption for which there is little confirmatory evidence. It would remain as a last expedient if all other explanations failed. A more plausible suggestion is that the valleys were excavated when the surface was more or less permanently frozen in Pleistocene times and could therefore support a surface drainage. We shall note that certain short valleys in the face of the Chalk escarpment are probably due to excavation by snow-melt water (p. 404), and there may have been similar action on the dip-slopes. But the application of this hypothesis to the whole of the dry-valley systems in no sense fits the facts. It implies that these valleys were a sudden and late accession to the landscape, whereas they behave in plan like a normal integral part of the regional drainage system (Fig. 171). Moreover, any general explanation has to fit not only the Chalk areas near the former ice-edge, which may have supported snow-caps and were certainly frozen, but also the French areas much

[Photo by A. J. Bull.

Fig 177—The Seven Sisters, Dry Chalk Valleys left "Hanging" by Cliff Recession, E Sussex.



[Photo by H M Geol Survey Crown copyright reserved

Fig 178—The Devil's Dyke, near Poynings Sussex, a Steep-sided Coombe in the Chalk, perhaps excavated under Conditions of Nivation (p 404)

farther south, where the former prevalence of these climatic conditions cannot safely be assumed.

There can be no doubt that Fagg has given the best general explanation of the dry valleys. His argument is based on the Chalk area of North-eastern Surrey. It rests on two simple facts illustrated in Fig. 172, viz. (*a*) that the general height of the water-table depends very largely on the level of discharge of the scarp-foot springs, *i.e.* the level of the Gault junction, and (*b*) that the escarpment has receded during the current cycle of erosion from a " feather-edge " on the uplifted peneplain whose remnants are now represented by the upland summits. During the retreat of the escarpment it has increased progessively in height, but the level of the Gault junction has evidently fallen steadily. Accordingly there must have been a secular fall in the water-table, independent of any change of climate, and valleys cut in earlier stages must necessarily have been abandoned later. It is possible to identify one former position of the escarpment by reference to the Limpsfield gravels (Fig. 172). When these were formed (by river action) they were at the *bottom* of the scarp-foot vale, of which the form may be reconstructed by projecting the escarpment forward from the present position. The geological date of the gravel (Middle Pleistocene) is given by its included palæolithic implements. For this date, therefore, we can reconstruct the water-table, assuming that its *general* form was as it is now. It at once appears that this would cause springs to break out in certain of the present dry valleys. An extension of the process backward in time accounts for other groups of dry valleys. Fagg's detailed analysis on these lines is complete and convincing, and has evoked no valid objections in the twenty years since its publication.

There can be no doubt that the above explanation of dry valleys is applicable in all Chalk areas of dip-slope type, and also in other regions where gently inclined sheets of limestone or sandstone form escarpments. Its great merit lies in its appeal to causes still acting demonstrably, if slowly. In this it is true to the tradition of " uniformitarian " geology and of the best deductive morphological arguments. Its acceptance does not preclude belief in the efficacy of other processes, which have no doubt cooperated in shaping the Chalk valleys. In particular it allows of the late intervention of nivation (p. 402) in the process, and also of the effects of solution guided by

joints or fissures.[1] The great Chalk area of Wessex (and similar tracts in France) may seem at first sight a stumbling-block to the argument, for it is terminated on the north and south by Tertiary basins, not by escarpments, and the escarpments on the east and west sides are widely separated. But it must be noted that the down-cutting of the Hampshire rivers has itself contributed to a steady depression of the water-table so that a similar process has been at work in " drying out " the minor valleys.

Karst regions.—Extensive tracts of compact or crystalline limestone exhibit underground solution phenomena which differ in degree, rather than in kind, from those of typical Chalk country. The jointing system in such limestones is commonly even better developed than in Chalk, and, moreover, the cohesion of the rock facilitates the opening of large caverns within it ; in Chalk and other more soluble rocks, such as rock-salt and gypsum, large caverns would tend very readily to collapse. The great limestone formations are, from the circumstances of their origin (p. 134), characteristically extensive and homogeneous. Variation in purity does occur, however, and affects the bulk of insoluble residue set free by solution. Such residues (the *terra-rossa* of South Europe) form slowly, and there is no doubt that with a dry surface and absence of vegetation, they are appreciably removed by wind. The occurrence of less soluble dolomitic and marly (*i.e.* clayey) beds in limestone is also important, as tending to check the downward penetration of water. It is evident that penetration will tend to a maximum when the bedding of the limestone is highly inclined, and such a check cannot operate.

The region in which underground drainage and related phenomena are best displayed, and have been most thoroughly studied, is the karst (It. *Carso*), which extends as a belt, some 50 miles wide and locally 8,000 feet high, from the Istrian peninsula south-eastwards through Jugo-Slavia, along the Adriatic coast. Surface drainage is practically absent, the only major river which crosses the

[1] The rectilinear plan of the dry valleys in many places suggests the influence of jointing upon the valley directions, but an examination of the dry valleys truncated by the Chalk cliffs in Sussex and Kent shows that there is no invariable relation of valley lines to recognizable fissures (Fig. 178.) The curious " nodes," or convergence points, of many tributaries, which occur in lines roughly parallel with the escarpments (Fig. 171) and largely influence settlement sites, probably mark halting-places in the retreat of the Tertiary edge down the Chalk dip-slopes.

belt being the Narenta (Fig. 179). So striking are the phenomena here that the term "karst" has acquired generic significance and has been applied in many other limestone regions. The corresponding French term is "causses," the causse regions flanking the Massif Central, revealing phenomena kindred, but not identical, with those of the Dinaric Karst. Milder manifestations of the same processes are seen in parts of the Jura, the Alps and the Apennines, in the Tertiary limestone of Poland, and the limestone country of England, Kentucky, Virginia, Central Tennessee, Northern Florida, and Yucatan.

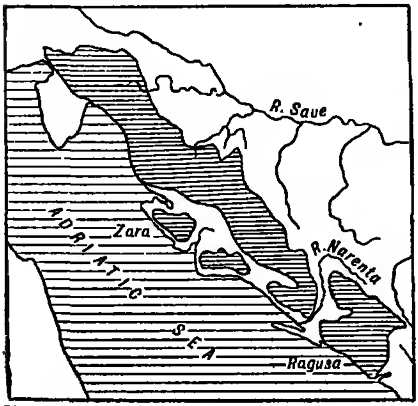


FIG. 179.—THE KARST AREA (SHADED) OF THE ADRIATIC COAST.

The morphological effects of surface and sub-surface solution in limestone are so distinctive that there have grown up parallel elaborate systems of nomenclature, deriving from local vernacular, for the description of land-forms, etc. Local British equivalents for most of the terms exist, but they have never been systematically collected and defined. As a result British, French, and German writings on the subject are exasperatingly studded with Serbian and other words which have taken on the status of technical terms. Apart from the needless air of obscurity or profundity thus conveyed, the practice is indefensible, for many of the words in question have much broader meanings than their technical use assumes and confusion inevitably results. It is interesting that the parallel local systems exist, but it should be unnecessary to burden writings in any one language with a polylingual jargon of ugly and ambiguous terms. Nevertheless the ground remains to be cleared, and we must perforce study, in passing, the synonymy of the nomenclature.

Bare limestone surfaces commonly show a widening of joints by solution, or, in extreme cases, a complex fretting or fluting of the surface, which rises in minor ridges and pinnacles separated by deep and narrow clefts. Limestone pavements tending to this type are called "clints"

or " grykes " in the North of England. The French term for such areas of " solution fretwork " (often to be crossed on foot only with great difficulty) is " lapiés " (Fig. 180); while the Germans speak of them as " karren " or " schratten." The Serbian term for deeper fissures is " bogaz." Swallow-holes are characteristic of the karst regions. They are known as " dolines " in the type karst (Fig. 181), as " sotchs," " creux " or " emposieux " in various parts of France.[1] Vertical or highly inclined shafts, leading from swallow-holes, or direct from the surface to underground caves, are " ponor " in the Serbian karst (Fig. 181) and " avens " in France, while many other terms are used.

FIG. 180.—LAPIÉS.

Depressions larger than swallow-holes and arising often through their coalescence are termed " uvalas "; there is no English equivalent. Uvalas may range up to a kilometre

[*After Cvijic.*

FIG. 181.—DOLINES LEADING BY WAY OF " PONOR " TO UNDERGROUND CAVES.

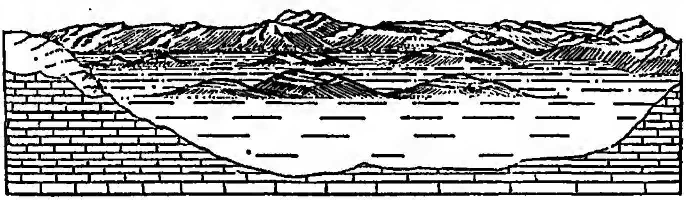
in diameter. Still larger depressions, some of rather problematical origin, are termed " poljes " (sing. " polje ") (Fig. 182). Some of these are formed by solution, and all are modified by its action. Residual limestone masses or hummocks rising above polje floors are called " hums " (Fig. 182).

The surface of a well-developed karst has lost all semblance of normal water-modelled forms. It is a stone desert, a chaos of pits, elongated hollows, and ridges; and

[1] Alternative English words are " swallet " and " sink," the latter being favoured in America.

devoid of surface-drainage save where allogenic streams cross it at the bottom of precipitous gorges, like that of the Tarn in the Great Causses of France. In less developed cases, more or less concordant dry valleys may exist, or elongated depressions, which are evidently "blind valleys" in process of abandonment (p. 292).

The common phenomena of limestone caves are too familiar to need extended description here. They commonly form part of a complex system of channels, widening locally into chambers, and fall broadly into two sets, viz. roughly horizontal galleries, and vertical or steeply inclined shafts, of which the higher members are the "ponors" communicating with the surface (Fig. 181). Some have supposed that such channels may be in general, though intermittent, use through the whole thickness of rock involved, water rising by siphon-action so as to flow through the upper galleries before descending. No doubt



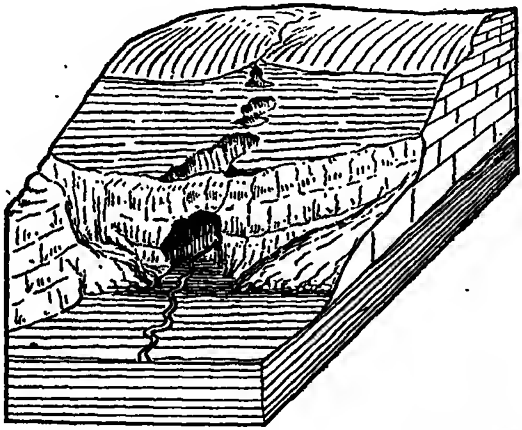
[*After Cvijic.*

FIG. 182.—A POLJE WITH RESIDUAL LIMESTONE MASSES.

this occurs to some extent; but in general we must think of the underground drainage as related to the permanent water-table. In well-jointed limestones, the water-table is characteristically flat and well below the surface, owing to the unusually free fissure-guided flow. The water-table is the general level of flow of the underground streams. It may oscillate in position with variations of surface supply, but above its highest levels the channels in the rock can only bring down intermittent storm-water. Complete underground river systems have been traced by such investigators as Martel, and the streams show many of the features of ordinary surface streams. They widen their course by mechanical corrasion as well as solution, for rock debris is washed in from the surface, and in flood they bring this action to bear on the roofs, as well as the sides and bottoms, of the galleries.

A good example of an actively eroding underground

stream, showing, by analogy with surface forms, many youthful features, is the Echo River of the Mammoth Cave of Kentucky. Such streams are often tributary to surface rivers, emerging at the foot of the steep valley walls as "Vauclusian springs."[1] Thus the Echo River flows into the Green River. In some cases the water-channels are partly above and partly below ground, as at Hann-sur-Lesse in Belgium. Such cases immediately suggest the possibility that buried streams may re-emerge to the light through the collapse of cavern roofs (Fig. 183). Examination of parts of Virginia confirms the suggestion, for here the process is incomplete and natural bridges still link the



[*After Cvijic.*

FIG. 183.—INCIPIENT STAGE OF VALLEY FORMATION BY COLLAPSE OF CAVERNS.

sides of gorges which have arisen by the deroofing of elongated caves. While this is one demonstrable origin of limestone gorges, there has been a tendency to overwork it as an explanation. Similar gorges can arise in the normal dissection of a limestone terrain, granted the requisite conditions of water-table, etc. De-roofing marks, in all probability, a phase of the karst process ; it does not go on everywhere and all the time.

The cycle of erosion in karst regions.—While certain karstic features are common to suitably placed limestone outcrops over a wide range of latitude and climate, the individual peculiarities of the major karst regions can only

[1] Named after the famous Fontaine de Vaucluse in South France.

be explained in terms of an orderly sequential development; in short, by the introduction of a cycle and stage concept. This was attempted by Cvijic for the Dinaric karst, the parts of which are in various stages of evolution.

Dealing with the matter in general deductive fashion, we may say that the pre-requisite condition for karsting is the existence of a thick and pure mass of limestone, resting upon an impervious stratum and with its surface well above the water-table. Thus a cycle may be initiated in two ways: (*a*) by the general uplift of a limestone terrain over which, before uplift, normal erosion was in progress, with the water-table near the surface; (*b*) the breaching, by a normal drainage system of the impervious cover of a thick limestone mass. In either case the enlargement of joints and the establishment of swallow-holes, etc., will at once begin in the upper parts of the mass. The swallow-hole, or doline, may, in fact, be regarded as the essential unit in karst morphology. By these means a portion of the surface drainage will pass below ground, though most of it remains on the surface. The further progress of the cycle involves the extension of solution in depth and the progressive increase of underground drainage at the expense of surface streams. The swallow-holes will increase in number and size, leading to growing caverns underground. Normal erosion will continue to act in the valleys above the points where the drainage "burrows." Thus will arise blind valleys—really "inverted hanging valleys"—which disappear underground below the level of their former continuations. It must be remembered, however, that the pitting of the surface by swallow-holes is not confined to the valley-floors, but goes on generally over the surface, destroying the former handiwork of flowing water. By the coalescence of neighbouring groups of swallow-holes uvalas will arise.

When all surface drainage has disappeared, pure karst conditions, *i.e.* the mature stage of the karst cycle, may be regarded as established. The passing of youth may be regarded as conveniently marked by the disappearance of the last traces of the former valley plan. In maturity a vigorous underground drainage has replaced the surface drainage, but this condition contains the seeds of its own dissolution. The continued opening of underground passages will tend to flatten and lower the water-table; the effective base-level of erosion is the surface of the underlying impervious bed. There is thus a limit to the

downward burrowing of caverns, and, since the general lowering of the land-surface by solution goes on unchecked, there will come a time when cavern roofs become too thin for stability and collapse. This is plainly the beginning of the end, that is, the re-establishment of surface drainage, which, given time, will revert to a " normal " condition on the impervious basement rocks. It is in these late stages that the smaller poljes must form, through collapse of cavern roofs and the mutual intersection of uvalas.[1] The residual " hums " are no doubt the last surviving remnant of cavern walls in many cases (Fig. 182). The periodic flooding of the deeper polje floors, as commonly witnessed in Yugoslavia, itself foreshadows the re-establishment of normal surface drainage.

Since the karst cycle, as outlined by Cvijic, is largely based on the phenomena of the Dinaric karst, one evidently invites the charge of begging the question in claiming it as the only fully developed karst yet studied in detail. Yet comparison with other European areas tends to enforce this claim. In the Dinaric karst the impervious base is below sea-level over considerable areas, the surface stands high, the limestone is pure, and the rainfall is considerable. In the Great Causses (Causses du Gévaudan), by contrast, the base rock outcrops in the gorges, and the total vertical scope for karsting is less. Whether for this or other reason the karstic development is much less perfect. True poljes are rare or absent, and the river gorges are due to allogenic supply, not to cavern collapse. In brief, the cycle is not so far advanced; and in any case, the general setting is against full development. The Little Causses (Causses du Quercy) depart even further from the type, for the limestone cover is relatively thin, and contains appreciable marly elements essentially impervious. In consequence, the dry valley plan is largely intact and forms " lines of verdure across the arid table-land, with arable fields climbing up the slopes and meadow-land in the bottom, which is often flooded after heavy rain." The

[1] One is loath to invoke solution as the cause of the major poljes, which range up to 50 km. in length and conform to the structural pattern of the country. Many of them are, in some part, tectonic depressions, Upper Tertiary basins filled with lacustrine sediments. On the other hand the fact that these large poljes show " tectonic " lineaments is not in itself a disproof of solution, for solution no less than corrasion is structure-guided. Where the walls and floors are of limestone, solution has undoubtedly helped in shaping them, but is probably not accountable for the whole of the depression. The term " polje " is applied popularly to depressions of varying natures, many of which are nothing more than ordinary valleys.

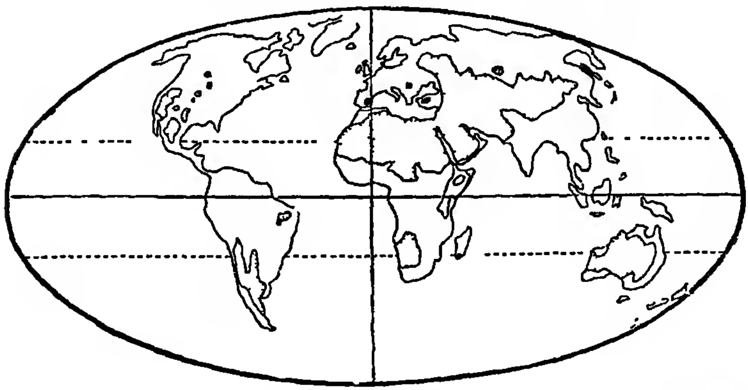
Little Causses have evidently not passed the youthful stage of the karstic cycle.

Comparable conditions exist in the limestone tracts of Britain. In the Mendips, Cheddar Gorge and Burrington Coombe, with their caves and swallow-holes, and the spectacular Wookey Hole with its " Vauclusian spring," show true karstic features. Again, in the Central Pennine area the middle platform of Ingleborough shows clint conditions admirably, while Gaping Ghyll is a typical " ponor " or " aven." The valley above Malham Tarn and the " Winnatts " above Castleton in the Peak district are " karstic " valleys, though there is no reason to regard them as collapsed caverns. In Ireland, bare limestone pavements occur at low levels. The proximity of the water-table here nips the karst process in the bud. The Chalk regions, if they can be fitted into the karst cycle at all, are evidently in a very youthful stage.

CHAPTER XX

EROSION UNDER ARID CONDITIONS

Introductory.—Our knowledge of erosion and land-sculpture under arid conditions is still rather severely limited by the incomplete exploration of the desert tracts of the world, and particularly by the general absence of accurate large-scale topographical maps of these regions. Notable contributions have, however, been made by J. Walther and certain French and English geologists in North Africa, by Passarge in the Kalahari, and by W. M. Davis and his followers in arid North America. It should, nevertheless, continually be borne in mind that our



[After De Martonne

FIG 184.—AREAS OF INLAND DRAINAGE.

acquaintance with areas of "humid" erosion is so much more detailed and exact that there is some natural tendency to over-emphasize the work of water. Essentially arid areas (chiefly basins of inland drainage) at present occupy approximately 30 per cent. of the continental surfaces, excluding the polar regions (Fig. 184). In the far geological past arid conditions prevailed over wide tracts now subject to normal erosion. Desert land-forms dating from these distant periods have locally been preserved beneath continental deposits, only to be exhumed by normal erosion in later times. Thus, as in the classic case of Charnwood Forest (p. 207), such land-forms have

become elements in the present landscapes. In the more recent past, since the last Pleistocene glaciation, arid or sub-arid conditions have widely transgressed their present boundaries, leaving their stamp on "normal" landscapes. The existing arid areas are sufficiently extensive of themselves to demand treatment in any balanced picture of earth-forms, but, as in the case of glaciation, the former migration of arid conditions lends further interest and importance to the study.

The physiographic form of the deserts of the world is very varied. The wastes of the Sahara, Arabia, the Kalahari, and Australia present general plateau forms of simple character, but many of the deserts of Asia and North America are mountain-girt basins. Climatically the tropical, or trade-wind, deserts owe their existence to the general atmospheric economy of the planet; aridity is imposed, independently of relief, by planetary factors. The intermontane basins lie, on the whole, in higher latitudes, and owe their extreme aridity, in part, to the rain-shadow imposed by bounding mountain ranges. It should be noted, however, that the "climatic" deserts would, apart from relief, tend to stretch into the temperate heart-regions of the larger land-masses; relief merely accentuates an aridity which would prevail in any case.

The border regions of the tropical deserts, where uninterrupted by salient relief features, show a perfect transition in physiography, as in climate, toward "normal" or humid conditions. Deserts of the "intermontane basin" type tend to be much more sharply bounded. "Normal" and "arid" erosion conditions may co-exist on either side of a narrow, but lofty, mountain barrier, the streams on one side draining to the sea and being subject to the control of a marine base-level, while those on the other, collect in temporary desert lakes (playas) or wither *en route* by percolation and evaporation. Hence, we obtain a truer first picture of the relation of normal to arid erosion by considering areas where a well-spaced transition exists, and where, therefore, the relative importance of the several factors involved changes slowly. The conception here involved is important. We can hardly accept for physiographic purposes any of the precise definitions of aridity proposed by climatologists.[1] How-

[1] These are based, in general, on the ratio of rainfall to temperature or evaporation.

ever we define the desert heartlands, there is, in most cases, a broad semi-arid margin in which processes and land-forms have clear affinity with those of the truly arid tracts. Such must be grouped with the deserts and afford most valuable clues as to the character of desert erosion.

Broadly defined, the essential factors controlling erosion in the arid regions are the absence of vegetation cover and the excess of evaporation over rainfall. In the tracts which " just divide the desert from the sown " it is readily seen that erosion is inversely proportional to the extent and thickness of vegetation cover.[1] In the absence of such a cover, the binding effect of roots is lost, while direct percolation, without surface-flow, is enormously increased. As we pass from these regions towards the desert interiors, drainage systems become increasingly open-textured and lose their integration, consisting of short dissevered streams which wither before reaching the sea or any main drainage trunk.

The processes of arid erosion.—We have already noted (p. 146) the salient characteristics of mechanical weathering, which reaches its maximum intensity in the true deserts. The insignia of the associated processes of transport and erosion are plainly written on the face of the desert, and it is true to say that they are well understood qualitatively, though ground for difference of opinion still exists as to their relative quantitative efficacy.

As the control of water-erosion diminishes, the work of wind, only locally appreciable in humid regions, increases in importance, though it is probable that it rarely becomes completely dominant over water-action. It is concerned in three distinct processes, viz. corrasion, deflation, and deposition.

Wind-corrasion is the work of strong air currents armed with sand grains. Its effects are imitated by the artificial sand-blast, which operates, however, under very different conditions. Quartz, the dominant mineral of ordinary sand, though softer than the gem-stones, is harder than

[1] In Hertfordshire, it has been estimated that the winter percolation (with vegetation cover reduced or absent) is eight times the summer percolation. We may recall, further, that the great deserts of the earlier geological periods were probably, in this sense, largely " biological " rather than " climatic " deserts. In pre-Devonian times there was no land vegetation, and for long after its first appearance such vegetation did not cover any large part of the land-surface, being confined to the vicinity of water. The spread of the *grasses* in Tertiary times has wrought powerfully against the extension of deserts.

most of the common rock-forming minerals. The long-continued, though intermittent, attack of wind-driven sand can polish or etch rock surfaces, if applied generally; or by localized action can produce fluting or channelling. Some measure of the action is given by the fact that steel rails can be cut through in time. The maximum corrasive effect is exercised some distance above ground level. Near the ground the wind is retarded by friction, while there is an upper limit beyond which normal winds will not lift sand grains of average size. Thus, though the limits doubtless vary in height, there is a general tendency to undercut upstanding objects. Wooden telegraph poles are quickly cut down in parts of the Australian Desert, while rock-masses assume a characteristic mushroom-form (*Pilzfelsen* of Walther). Where such masses are

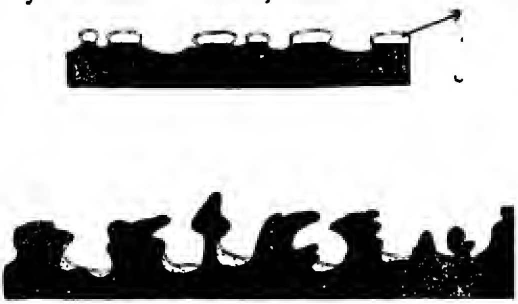


FIG. 185.—SOME EFFECTS OF WIND-EROSION.
Above, Zeugen; *below*, Yardangs. Zeugen vary from 5 to 150 feet in height.

tabular in form, consisting of a table of some harder stratum on a pedestal of shale, mudstone, etc., they are known as *Zeugen* (Fig. 185). With complete removal of the pedestal the mass is overturned and the process starts anew. Other striking features produced by wind-corrasion are the "yardangs" described by Sven Hedin from the Central Asiatic desert (Fig. 185). These are steep-sided rock ribs, up to 20 feet high and from 30 to 120 feet in width, separated from one another by grooves or corridors cut in the desert floor. Though irregular in form and with undercut sides, they maintain a rough parallelism over considerable areas. It cannot be doubted that they owe their origin to veritable æolian corrasion, under the influence of steady winds.

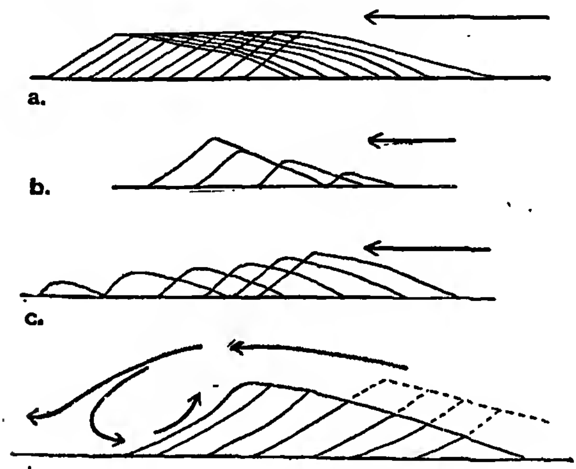
Loess.—The name "deflation" (Latin *deflare*, to blow away) was applied by Richthofen to the process of win-

nowing the finer material from the desert floor. The dust storms of the desert are familiar in word and picture and much of the dust thus raised is dropped again locally. There is ample evidence, however, of actual export of dust from arid regions. The so-called blood-rain, which falls occasionally as far afield as North-western Europe, is tinted by Saharan dust, and the sails of ships off the west coast of Africa are reddened from the same source. Wind-blown desert particles are almost the only terrigenous elements found in the deep-sea deposits. But much more eloquent of the magnitude of export by deflation are the great masses of *loess*, first described by Richthofen in China. Alike in its physical characteristics, and its occasional fossil contents (land animals), this remarkable deposit of fine-grained yellow dust reveals itself as a wind-blown deposit. It has accumulated to a thickness of 400 to 1,000 feet, filling the valleys and burying the hills of Northern China. It is evidently the export from the arid wastes of Central Asia.[1] The curiously small scale vertical jointing of loess has been attributed, in part, to the influence of vertical plant roots, and it is probable that a vegetation cover has assisted in trapping the dust during the accumulation of the deposit.

Dunes.—The great loess deposits not only give some measure of the deflation process, but also illustrate the local importance of æolian deposition in desert borderlands. Deposition of coarser material occurs within the desert, notably in the form of the characteristic dunes. Much has been written on the formation and general economy of dunes. The coastal dunes of temperate latitudes are more accessible for study, but they are not strictly comparable with desert dunes, being smaller and less fully nourished with sand. Few of them are active or migratory, owing to natural or artificial fixation by vegetation, particularly marram-grass (*Ammophila*

[1] It should be noted that the loess of Europe accumulated during the phase of temporary aridity, and reduced vegetation cover, associated with the Pleistocene glaciation, and thus it may not be strictly comparable with the Asiatic loess. Some have supposed that it accumulated during the Ice Ages, beyond the margins of the ice-caps. But some of the loess appears to be inter-glacial—*i.e.* accumulated during the warm and relatively dry intervals which separated the actual glaciations (p. 407). At these times wide stretches of sandy outwash plain were available for wind attack. It is possible, though not as yet proved, that the Asiatic loess was also associated with the Pleistocene glacial conditions and is not, as it were, the normal export of the Asiatic deserts. In any case, the European loess affords an example of temporary arid conditions unconnected with the true deserts.

arenaria). Special conditions, including broad stretches of shore sand, bared at low water and subject to the influence of on-shore winds, are necessary for their initiation. Active supply is only available intermittently, when the sand-surfaces dry after low water, and in general the winds are less constant than those of the desert regions. Nevertheless, the larger coastal dune-tracts, such as that of the Landes in South-west France, present phenomena comparable with those of the sand deserts.



[*After Sven Hedin.*

FIG. 186.—TRAVELS AND GROWTH OF DUNES.

(*a*) Regular advance with constant supply. (*b*) Advance decelerating, with increasing height and sand supply. (*c*) Advance accelerating, with decreasing height and sand supply. (*d*) Influence of wind-eddy on sand-fall face.

The dunes fall into two classes, transverse and longitudinal, according as they lie roughly perpendicular to or parallel with the prevalent wind direction. The transverse dunes are characteristically asymmetrical in profile, with their gentler slope towards the wind (Fig. 186). Sand is driven up the windward slope and descends the steep "sand-fall" under gravity, though a wind-eddy in the lee of the crest probably tends to retard the descent and affects the form of the sand-fall slope, tending to hollow it and thus impart to it a concave profile, in contrast with the convex profile of the windward side. In plan the crest-line of the dunes tends to be arcuate, the convex side of each arc being turned to the wind and the crest standing highest near the centre of the arc: in other

words, the lower ends of each eminence in the dune-ridge tend to curve down-wind (Fig. 187).

The mode of origin of longitudinal dunes is less obvious at first sight, but, in some cases at least, it appears that they arise through the modification of transverse dunes. The latter become fixed by binding plants at the lower points, or cols, where the water-table (p. 269) is nearer the surface. With the ends thus fixed the arc is, in effect, blown inside out, *i.e.* the wind continues to drive the central higher part of the dune onwards, turning the original convexity into a concavity. With a continuance of this action, particularly when sand supply is deficient, a " blow-out " may arise at the head of the bay, and the dune will thereafter consist of two separate arms inclined towards each other. Ultimately these arms are rotated so as to point directly down-wind, becoming true longitudinal dunes. It is probable that longitudinal dunes can also arise by the growth and down-wind elongation of small sand hillocks, trapped initially by low-growing clumps of vegetation.

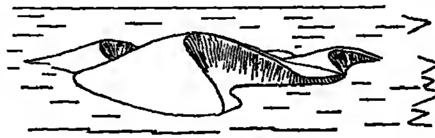


FIG. 187.—BARCHANS (CRESCENTIC DUNES).

[*After de Martonne.*

FIG. 188.—THE AREAS OF SANDY DESERT IN THE OLD WORLD.

The study, still far from complete, of dune-formation in the desert has led to the recognition of forms and phenomena analogous to those of the coastal dune areas. " Barchans," isolated crescent-shaped dunes, transverse to the wind and with down-wind horns, are well developed in parts of Turkestan, though only to a limited extent in the Sahara (Fig. 187). The sand areas of the Old World deserts (" Erg " of the Sahara, " Koum " of Asia) are well defined and strictly localized, forming comparatively small islands in the stone or rock desert (" hamada ") (Fig. 188). In some places a featureless sand veneer may

cover the surface, but, more typically, the sand areas are a maze of dune-ridges. Aerial photography resolves the seemingly chaotic arrangement, as viewed from ground level, and shows that the dune complexes consist on the whole of sinuous transverse dune-ridges—in effect, strings of barchan-like features which have coalesced. Though each individual dune migrates down-wind, the dune complex as a whole remains essentially stable in position and area. Locally, longitudinal dunes are found within the mass, particularly in the neighbourhood of the long narrow corridors which traverse the complexes for long distances and are often followed in the Sahara by caravan routes. Such features, no doubt, arise through localized wind-erosion ; they represent, in effect, aligned "blow-outs," and the dunes are slewed round into longitudinal positions in their vicinity.

The localization of the dune-areas appears to be related to the form of the underlying surface and the sand-supply. They generally occupy slight depressions, where the first stages of growth may have been assisted by a moist or temporarily water-covered surface. They form in the lee of tracts of sandy river alluvia or disintegrated sandstone outcrops.

General results of wind-action.—If we now inquire into the general characteristics and probable ultimate results of wind-action, we shall find a wide field open to doubt, and a pressing need for much more detailed quantitative work. Deflation is the only means whereby the surface of an arid region can be lowered by bodily removal of material from the region. The question thus arises : what is the general speed and efficacy of this process as compared with water-erosion ?

There are a few facts and figures to help us, but they do not carry us far. The calculations of J. A. Udden showed that in the great storm of 1895, 4 to 10 tons of dust per square mile were desposited in Indiana. More generally, he estimated that 850 million tons of dust were carried 1,440 miles each year in Western United States. From another region comes the interesting estimate of Sir Flinders Petrie that 8 feet of material have been removed by wind from the surface of the Nile delta in 2,600 years. These amounts appear large, but it is generally agreed that they represent a much slower levelling process than that of water-erosion. It is tempting, indeed, to emphasize the obvious fact that wind-action is only in a minor degree

constrained by the form of the ground. Its potential field of action appears to be the whole surface, and its relation to water-action might seem to be that of the sand-paper to the file. But this antithesis is largely false. The localized file-like action of vertical water-corrasion is assisted by general "atmospheric wash"—the flattening of slopes—and after maturity is reached the land-levelling processes are generally, not locally, applied. Moreover, there is definite evidence that wind does not act constantly over the whole desert-surface. In North Africa old tracks and encampment sites may remain unobliterated for many years, clear proof of differential action.

This leads us to the related question of the characteristics of wind-sculpture. In detail, it is clear that wind-corrasion sharpens the relief forms, etching out geological structure with marvellous clarity. The "arid south-west" in the United States has contributed greatly to our understanding of geological structures of various types, and we may recall, too, the limestone folds of the Persian oil-fields, which stand out in simple relief in most impressive fashion. Thinking in more general terms we may say that a salient tendency of wind-sculpture is the steepening of the bases of slopes. If water-action intervenes, they may be graded by wash (p. 176); but in its absence, masses large and small, rise sharply from the desert-surface, giving the characteristic "Inselberge" (p. 309) of South Africa, Nigeria, etc. (Figs. 191, 192).

Apart from these general effects, differential wind-erosion can evidently produce small hollows. Can such hollows become large enough to rank as land-forms? In the limestone plateau west of the Nile Valley, the oases occur on the floors of curious depressions lying from 300 to 1,300 feet below the surrounding country. The winds of the district are northerly, and in general the northward facing slopes grade up gently into the desert-surface. Wind-action is sufficient to check accumulations in these hollows at present, and some have supposed that they owe their origin to wind-erosion. Such a hypothesis presents certain evident difficulties, and an alternative suggestion has been made that the basins are the result of a sort of "trap-door" faulting. Again, since these hollows occur in a limestone terrain, it is far from improbable that solution has had a hand in shaping them. Shallower depressions, such as the "salt-pans" of Northern Cape Colony, West Australia and Arkansas are more

plausibly attributed to wind-erosion, though in the last-named region, and possibly in others, the depressions may be nothing more than "buffalo-wallows," from which, in time, the beasts removed large quantities of mud.

On the whole it must be conceded that we have no evidence that the wind can excavate steep valley-like forms on any appreciable scale. Shallow depressions produced by deflation are of a different category, yet even here the extent of wind-action is in doubt.

We must postpone consideration of the eventual results and limits of wind-erosion till we have reviewed the co-operating activities of water in the desert.

Water-action in the making of desert relief.—In semi-arid regions, with a moderate rainfall of some·15 inches annually, water-dissection achieves notable results in areas of soft impervious rocks. Unchecked by the distributing action of a turf cover, myriads of water channels arise and the country is carved into the condition of typical "bad lands" or "scab-lands."[1] The existence of such landscapes is a warning against under-estimating the effects of water-action in the true deserts. In no case are the latter absolutely rainless, and the rainfall is very heavy when it occurs. The stream courses function in carrying off the occasional floods, which, as many a traveller's tale assures us, are often disastrous in their suddenness and violence. But a flood is short-lived, withering by evaporation and percolation. While it lasts it can pick up great quantities of comminuted rock material lying ready on the surface, but it quickly loses the means of transportation. Starting downstream as a flood of turbid water, it becomes by degrees a pasty mass of rock-debris, lubricated by water, and as the lubrication fails the mass comes to rest. It is characteristic that the more permanent river courses of the deserts and desert margins are marked by exceptionally bulky alluvia. Moreover, the widely separated and disjointed water-channels of the desert are often inadequate to carry off the local heavy rains. Such rains on moderate slopes may

[1] Within the true deserts there are much-channelled areas, such as the "chebka" of the Sahara, which seem to have passed through a "bad-land stage." Greater aridity has stopped or checked the process; the channels are no longer mutually accordant and have lost all semblance of organized drainage plan. The phenomenon speaks clearly of recent climatic change within the deserts and we shall find that such changes are of great importance in interpreting desert landscapes (p. 306).

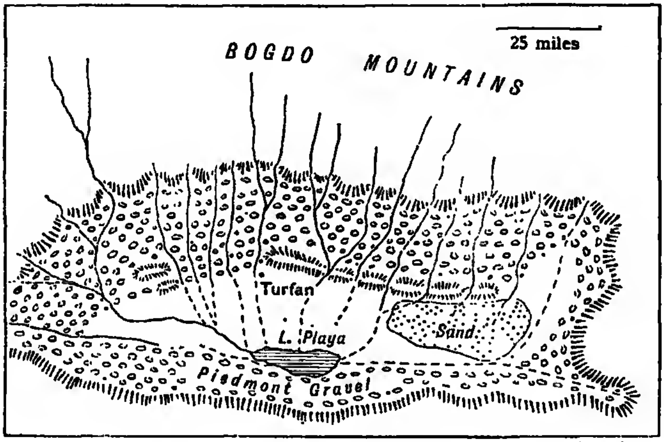
fail to subdivide into definite channels, passing downhill as a " sheet-flood." These, like the stream-floods, come to rest through loss of water, leaving in some cases a low moraine-like ridge on the plain, parallel to the highland margin.

It is seen, therefore, that water-action in the desert gives rise to notable effects in deposition. Temporary moving water-masses are immediately provided with more load than they can handle; they are " underfit " from the moment of birth, and die of a species of " alluvial suffocation." Their short life and impeded movement must evidently restrict their power of vertical cutting in bed-rock, though we shall note below evidence of lateral corrasion. One of the most general actions which can be attributed to the water in the desert is the tendency to fill, by wash, any hollows created by wind-action, and thus to oppose, when opportunity offers, the dominance of the latter element.

The building up of " piedmont fringes " of coarse sediment, essentially screes and alluvial fans, by combined sheet-flood and stream action is naturally more characteristic of intermontane basins than of the broad plateau deserts, and excellent examples are afforded in Asia. The great Tarim Basin stretches for 1,400 miles from Kashgar to Su-Chow, and is 400 miles across from north to south. It is bounded on all sides by lines of faulting or monoclinal flexures, which separate it from the ranges of the Kwen-lun and Karakoram Plateau on the south, from the Pamirs on the west and the Tian-Shan on the north. The centre of the great basin receives a slight snowfall and heavy summer showers, but at an elevation of 10,000 feet on the bounding mountains a moderate rainfall occurs, locally supplemented by snow-melt waters in spring. Thus is initiated a centripetal drainage towards the central playa-lake of Lop Nor. For the greater part, this drainage does not reach its terminus, but withers in the broad piedmont zone of gravel—5 to 40 miles wide—which follows the highland boundary.[1] The smaller basin of Turfan lying to the north-east repeats almost exactly the features of its larger neighbour (Fig. 189).

[1] The water emerges at the inner edge of the piedmont gravel in springs and can be tapped at shallow depth throughout the " toe-region " of the piedmont. Here is the zone of vegetation and settlement—a fairly constant feature in basins of this type.

We must note, finally, the important evidences of *former* water-action in the desert. It has become clear that parts of the tropical deserts (*e.g.* Libya) reveal water-cut valleys with overlapping spurs, etc., which cannot be attributed to the feeble and sporadic water-action now proceeding. Such features, indeed, constitute clear morphological evidence of a past "pluvial period," but much other geological evidence of such periods has latterly come to hand. Broadly speaking, it appears that the circumpolar expansion of glacial conditions in Pleistocene times involved the displacement of the other climatic belts, so that, at times, the temperate rain belt extended



[*After Huntington.*

FIG. 189.—THE TURFAN BASIN.

over the present desert regions. In other words, we have reason to think that a glacial period in high latitudes may have been represented by a "pluvial period" in the deserts. Since the last great North European ice-sheet began its retreat only 25,000 years ago (p. 410), it may well be that the prevailing extreme aridity of parts of the desert has been comparatively short-lived, though there may have been former arid episodes in the inter-glacial periods, corresponding to the one in which we are now living. The important bearing of such climatic alternations, if they can be proved, on the interpretation of desert landscapes, needs no emphasis.

The erosion-cycle in an arid climate.—We come lastly to the important question: Is a distinct series of cyclical

changes perceptible or expectable in arid erosion? Thirty years ago W. M. Davis sketched the theoretical cycle in outline, admitting that many of his deductions could not then be matched in actual observations. This is still true in part, but we shall find it useful to describe the broad features of the deduced cycle, as a summary and extension of the foregoing paragraphs.

In theory, arid conditions might supervene upon any kind of initial surface. Since, however, few, if any, of the processes of arid erosion tend markedly to increase relief (*i.e.* there is little vertical corrasion), to start with a surface essentially level involves us in difficulties. If any of the great plain or plateau deserts began life as surfaces of low relief, it is probable that they have rarely departed far from their original condition. In early stages the surface would be cumbered with rock-debris, but progressive comminution of the material combined with steady deflation might result in a rock-plain. The passage from the initial surface to an "æolian peneplain" would presumably be accomplished within a small range of vertical levels. Whether wind corrasion, combined with deflation, can in time bodily cut a country down to a markedly lower level is at best doubtful.

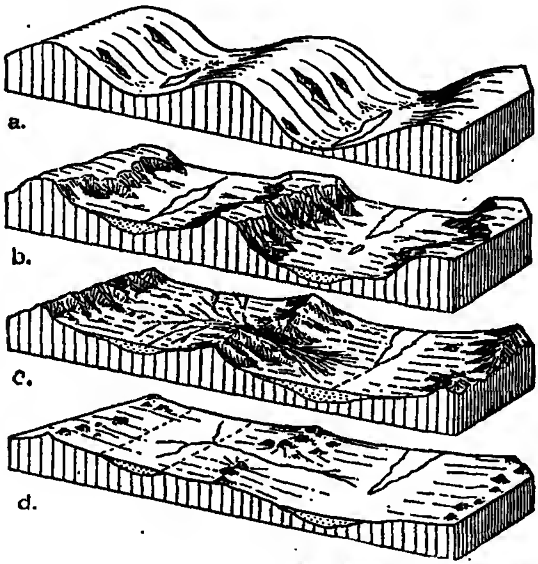
We can obtain a clearer notion of the cyclical interaction of the processes at work by considering the simpler case of initial intermontane basins, formed by earth-movement. Here we start with an appreciable initial relief, and we can reconstruct the probable changes in morphology with reasonable certainty, checking our deductions by reference to such regions as the Basin Ranges of the United States or the larger intermontane basins of Asia.

The initial uplift would provide a number of independent mountain-girt basins, in each of which would arise a centripetal consequent drainage, for which the several basin-floors would serve as effective local base-levels (Fig. 190). In truly arid conditions, only by chance could communication be quickly established between neighbouring basins, for evaporation would check overflow and many streams would, in fact, wither on the basin slopes. Only in any cooler season, or as a result of exceptional floods, would a temporary central playa come into existence.

During the youth of the cycle (Fig. 190), relief would be slowly diminished by the wash of the highland slopes into

the basins, which would be steadily filled. This would cause the local base-levels to rise and hence. as time progressed, the filling process would be retarded. Wind-transport would in part contribute to the filling, though widespread deflation might work slowly to reduce highland and basin-floor alike.

With the aggradation of the basin-floors and the reduction of the separating heights by erosion and burial, some of the barriers might well be cut through by head-water erosion of major gullies (Fig. 190). Thus, higher



[After Longwell, Knopf and Flint.

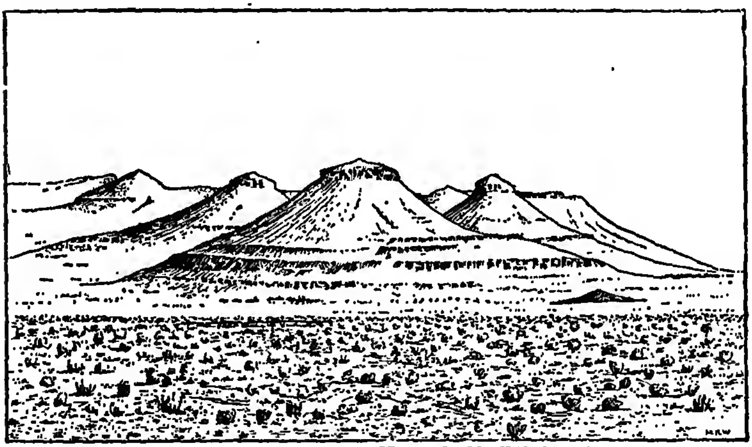
FIG. 190.—STAGES IN THE CYCLE OF ARID EROSION.

(a) Initial stage showing playas and incipient fans in intermontane basin. (b) Youth; relief decreasing as basin floors rise. (c) Maturity; capture of higher by lower basin. (d) Old age; low relief and disintegration of drainage.

basins would become tributary to lower and a rough integration of the drainage would become apparent. This might reasonably be taken to mark the passage to maturity. A result of this action would be that the floors of the higher basins would be dissected and their filling transferred to lower basins.

With the advance of maturity and the continual degradation of relief, water-action would diminish, as both rainfall and slopes diminished. Wind-action, active from the beginning of the cycle, would now rise to

dominance, and export by deflation would assume large proportions. We might expect, therefore, the removal of the alluvial veneer where it was thinnest, towards the margins of the basins, and the exposure of bare rock (Fig. 190). In this, the wind, acting alone, might be expected to carve slight erosion hollows which might interfere with the plan of the drainage and ultimately disintegrate it. Such action, proceeding in marked degree, would produce an irregular "hill and hollow" topography, examples of which are in fact hard to find. It is probable that water-wash in most cases tends to fill such hollows, and thus maintains the essential flatness of the plain-surfaces.

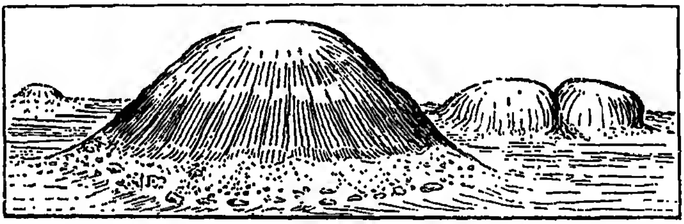


[*Drawn by M. Wells from sketch by A. K. Wells.*

FIG. 191.—THE THREE SISTERS, VICTORIA WEST, CAPE PROVINCE.
Inselberge eroded in shales of Beaufort Series, capped by dolerite sheet.

The late stages of the cycle.—So far we have proceeded by deduction. The earlier stages of the deduced cycle can be matched in many places; but considerable dubiety has existed concerning the stage of old age and the true character and origin of the ultimate plain feature, if any. As long ago as 1904 Passarge, in his studies of arid South Africa, noted the existence of vast flat surfaces studded with sharply rising residual hills, termed in German literature "Inselberge" (Fig. 191). He regarded such surfaces as marking the limiting forms of a long period of arid erosion, supposing that export by deflation must produce a plain below the level of the deepest of the initial basins, a rock-floor thinly

veneered by waste. Such a surface would be independent of the normal base-level in a region of inland drainage. The downward limit, if any, to the work of corrasion and deflation under arid conditions would be set by the water-table. On this view surfaces of arid planation might arise above or below sea-level. If interpreted as normal peneplains their present attitude would in many cases imply strong subsequent uplift. This corollary of Passarge's work was emphasized by W. M. Davis, who pointed out that origin at a high level under arid conditions must always be borne in mind as a working hypothesis when considering the history of summit-planes. In recent years O. T. Jones has suggested the possibility that the great Welsh summit-plane (p. 216) may represent the continuation of the sub-Triassic surface, formed under arid conditions. The acceptance of this suggestion would obviate the necessity of assuming subsequent uplift to



[*From photographs by A. D. N. Bain.*

FIG. 192.—GRANITE DOMES (INSELBERGE) NEAR LEMME, NIGERIA.

the full extent of its present elevation. The possibility is interesting but has, in the view of the present writers, little evidence to support it.

Surfaces comparable with those described by Passarge in Bechuanaland and its region are widespread in the African Continent. A plain, cut in massive gneissose rocks, and diversified by steep-sided residuals, occurs widely in Uganda. Similar conditions exist westward of the coastal plain in Mozambique. In Nigeria there are extensive rock-plains from which rise Inselberge in the form of remarkably regular granite domes (Fig. 192). The association of Inselberge and flat rock-plains, with or without a thin veneer of sand or gravel, is thus an amply established fact of observation. Passarge's explanation, which puts the major emphasis on æolian deflation, has not found favour with later workers. There is little doubt that deflation, co-operating with sporadic rains,

can produce a flat surface on the fragmental accumulations of the desert, but it is now clearly established that planation has often occurred also in solid rock. The crux of the discussion lies in the origin of these rock-plains and the associated Inselberge. It has never been credibly demonstrated that simple æolian action can cut an extensive flat surface in hard rocks, nor that it is primarily responsible for Inselberge. The latter have evoked very diverse explanations. Some have regarded them as the product of complex alternations of humid and arid erosion, while others, particularly among the German geomorphologists, have treated them as entirely analogous to monadnocks, the residuals of humid erosion. We shall return to the African case below, but to follow the later progress of theory we must turn to the great arid areas of North America, where notable work has been done.

North American arid landscapes.—Truly arid conditions extend over the greater part of the great " median " plateaux of the South-west United States, and the erosional results are exceptionally well seen in the Basin and Range Province in Nevada and Arizona, and in the contiguous tracts of New Mexico and Sonora, beyond the Mexican border (Fig. 193). Over much of the area, fracture gave an initial topography of tilted fault-blocks separated by intermontane plains, and the conditions thus resemble those envisaged by Davis in his theoretical scheme (p. 307). As compared with arid Africa, plains are here in a much less dominant role; we have an intermont-basin landscape as compared with a true Inselberge landscape. Nevertheless, plain-surfaces of various kinds are still very important, accounting, in the opinion of Blackwelder, for three quarters or more of the total area. The flat surfaces of the American desert-plains comprise, in the first place, the relatively limited areas of river flood-plains, cut in rock or built of alluvium, and of playa floors.[1] Between the margin of the latter and the foot of the steep mountain walls are gently sloping surfaces which prove on analysis to belong to two types which, however, frequently occur in association. The first type is the " bajada," plainly due to aggradation by floods debouching from the mountain valleys (cf. p. 170). Bajada plains are underlain by thick accumulations of coarse alluvia. In detail they thus

[1] We may also distinguish structural rock-benches which arise from the very complete stripping of overlying softer from underlying harder rocks, under the conditions of arid erosion.

reveal themselves as formed by the confluence of alluvial fans. The radial profile of the individual fans is concave, but a traverse parallel with the mountain foot reveals an undulating profile, for each fan is gently convex in this direction. The second type is the inclined rock-floor or "pediment." This may be thinly strewn with gravelly alluvia in such fashion as to conceal its real nature on casual inspection. The essential flatness of the surface

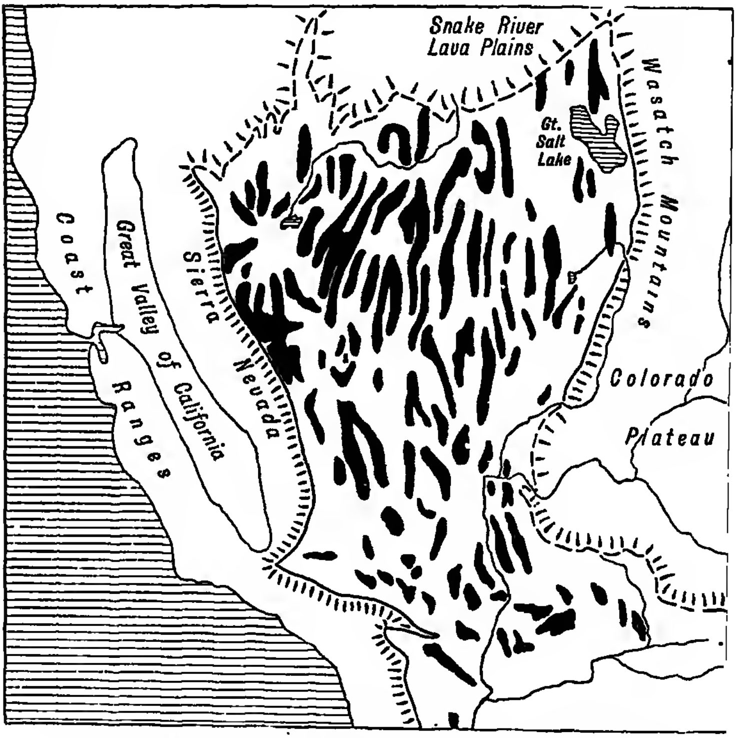
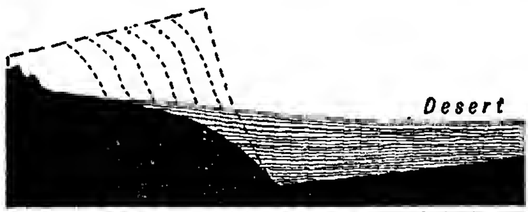


FIG. 193.—THE BASIN RANGE PROVINCE OF S.-W. UNITED STATES. Fault blocks in black.

reflects, however, a genuine planation of solid rock, often of the same character as that which forms the neighbouring mountain range. Blackwelder states that the radial profile of pediments in United States is almost imperceptibly concave, with gradients ranging up to 7°, though averaging about 2½°. The profile parallel to the mountain foot is regarded by him as essentially straight or flat, thus contrasting with a typical bajada.

THEORIES OF PEDIMENT FORMATION

Features comparable with those now known as pediments were first noted by Gilbert in his classic rescarches on the Henry Mountains of Utah. Further work in Arizona, Sonora, and New Mexico has shown that they are a consistent feature of the desert landscape, and various suggestions have been made as to their origin. McGee attributed them to the erosive action of sheet-floods (p. 305), which certainly occur in such regions. Though few would deny the ancillary influence of sheet-flood action once the pediment slope is in being, it seems unlikely that pediments are in any sense initiated by sheet-floods. Lawson, and later Bryan, supposed that the pediment originated through the recession of the mountain front under the influence of the ordinary processes of arid erosion. Thus, while it continually extended backwards



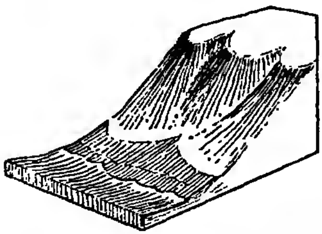
[*After Lawson.*

FIG. 194.—ORIGIN OF PEDIMENT OR "SUB-ALLUVIAL BENCH" BY RECESSION OF MOUNTAIN FRONT.

at the expense of the receding mountain country, its frontal edge was encroached upon by the alluvial filling of the intermont depression (Fig. 194). On this theory the extent of exposure of bare pediment at any given time would depend on the relative rates of mountain recession and alluvial encroachment. In the limit of such a process the mountains would disappear altogether and the thin feather edge of the alluvial " fill " would mantle the whole of the pediment. Lawson's term for the latter, " sub-alluvial bench," arose naturally from this conception, and as a further corollary he supposed that the rock-floor could only appear at the surface by exhumation from beneath its thin cover. This might follow from climatic changes, or, more generally, from long-continued æolian deflation.

Davis accepted in essentials Lawson's theory of pediment formation, and endeavoured to show that the process was generically linked with that producing rock-plains in humid

climates. His argument was largely deductive and aimed to show that, despite the important differences due to climate, humid and arid erosion were kindred, the latter being, as it were, a special type or extension of the former He identified the gently sloping ground above humid river flood-plains—the " valley-floor basement " (Fig. 195)—with the pediment of arid piedmont zones, and he argued that an extension of such a surface, by recession of the valley slopes, was an important element in " normal " planation. His views appear open to criticism on several grounds. The extension and coalescence of valley-floor basements, thus envisaged, is, in reality, a novel addition to the theory of peneplanation under normal erosion, and, as such, it finds no explicit place in the earlier writings of Davis and other workers. The present writers can see little evidence that any such process shares appreciably in the work of normal peneplanation. Pediments are best developed at the foot of granitic block mountains. Davis admitted his inability to cite any granitic " block mountains " subject to humid erosion in which comparable effects might be sought. It seems fair to note, however, that many granitic bosses, standing sharply above surrounding lowland, offer some parallelism with the postulated conditions, but they do not appear, in any case known to the writers, to exhibit expanded valley-basements of the deduced type. It would hardly be fair argument to dismiss them all as too youthful in stage to show the required effect. The actual instances adduced by Davis to illustrate basement-formation on a large scale are the great strike-vales or lowlands of the English and French scarplands and some of the older valley-floors of the Appalachians, below which the existing streams are incised. The former, typified by the inner vale of the Weald, are, in fact, rolling lowlands with a close dendritic drainage network. They are closely approaching the stage of true peneplanation, but there is little to suggest that they are expanded valley-basements, save in a very complex and special fashion, and they present but little analogy to arid pediments. The Appalachian valley-



[*After Davis.*

FIG. 195.—A VALLEY-FLOOR BASEMENT.

floors have, in many cases, been termed peneplains and in all probability reflect important phases of lateral river planation. It is hardly easier than in the case of the European lowlands to regard them as the homologues of pediments. It seems, therefore, that while the general case for homology between arid and humid erosion may stand in broad essence, its application to basement and pediment formation needs, as yet, much stronger evidence to support it.

Apart from the special turn given to the argument by Davis, the theory of pediment formation by mountain front recession leaves many points obscure or doubtful, and it is therefore interesting to notice that Gilbert, in his first encounter with the phenomenon of pediments in Utah, adumbrated an alternative explanation based upon water-erosion. He noted that the heavy loading of streams in arid regions reduced their power of vertical corrasion, and wrote : " Where the load reduces the downward corrasion to little or nothing, lateral corrasion becomes relatively and actually of importance. . . . The process of carving the rock so as to produce an even surface and at the same time covering it with an alluvial deposit is the process of planation." In recent years several authors have returned to the advocacy of some form of water-erosion as the prime formational influence in pediments. Thus Berkey and Morris, reporting on the piedmont rock-floors of Mongolia, ascribe the chief role in eroding the slopes to " the myriad short-lived streamlets acting on the weathered rock of the piedmont," and remark, further, that the whole slope " is lowered very gently as graded streams cut downwards." Similarly, Blackwelder, in a general review of desert plains, concludes that " pediments are essentially compound graded flood-plains excavated by ephemeral streams," and that the completed pediment to which Lawson applied the term " panfan "[1] is " the desert-inhabiting species of the genus peneplain."

The most explicit application of a theory of water-erosion to the problem is that of D. W. Johnson, who has revived and extended Gilbert's original suggestion. He accepts

[1] The term " panfan " signifies " all fan," and was applied by Lawson to the low rock dome which he conceived as arising from the continuance of mountain-front recession to the limit (Fig. 194).

Objection has been made to it on the ground that " fan " suggests an alluvial accumulation. This objection can have no weight if Johnson's argument, summarized below, is sound, for it leads to the recognition of " rock fans " as a normal product of arid erosion.

the probability that lateral corrasion is dominant throughout arid regions of the type we are considering. In the mountains, however, where the stream courses are steeper, there is sufficient downward corrasion (degradation) to mask the dominance of lateral corrasion. Similarly, in an alluvial zone, remote from the mountain foot, the palpable evidence of aggradation strikes the eye, though considerable lateral corrasion must, in fact, take place. Between these two regions is the typical pediment zone, where lateral planation is plainly dominant and where, since the streams are at grade, it takes place at a practically constant level (Fig. 196). A thin veneer of alluvium may accumulate in places on the slope, but is readily removed in the course of lateral shifting of the streams. It is a familiar fact that the intermittent streams of such regions descend the slope in complex braided courses subject to continual change. Though the process is rarely seen at work during

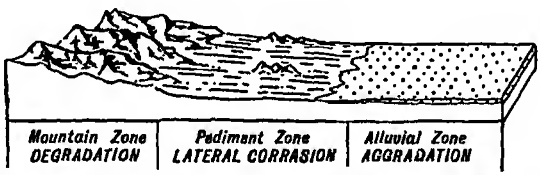


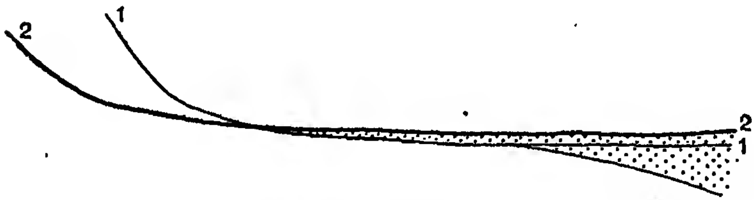
FIG. 196.—JOHNSON'S THEORY OF PEDIMENT FORMATION.

man's brief traverses of the desert, over a long period lateral planation is brought to bear on most parts of the surface. Johnson attributes the recession of the mountain wall to streams temporarily diverted against, or along, its foot, and the isolation and ultimate destruction of Inselberge to the same process.

A most important corollary, which provides an *experimentum crucis* for the theory, was deduced by Johnson. If pediments are water-cut surfaces, examination in detail should reveal rock-surfaced fans with their apices at the points of debouchment of the streams from the mountain wall. Below these points the streams have the choice of an infinite number of "radial" courses over the pediment, all of which will be occupied at some stage during a long period. We might, therefore, expect to find the pediment rising in low semi-cones along the mountain foot, the radial profile of such cones being faintly concave. Rock-fans of this type in Southern Arizona and Northern Sonora were noted, but without comment, by McGee as

long ago as 1897. Johnson has found well-developed rock-fans at the foot of the Sierrita Mountains near Tucson, Arizona, and at other points in the arid region. The examples he adduces go far to vindicate his deductions. Admittedly the number of proved rock-fans is as yet small, but it should be noted that since they are commonly hidden beneath a thin alluvial cover they are apt to escape notice on casual scrutiny, being mistaken for the familiar alluvial fans of normal type.

Johnson's theory is presented with his customary moderation of statement, but it has certainly established its claim to rank as a working hypothesis. If it proves applicable to pediments as a class, their profile along a line parallel with the mountain foot should be undulatory, as in the case of bajadas, not straight as supposed by Blackwelder. The profile from top to toe of the slope should be concave, as indeed is demonstrably the case in



[After Johnson.

FIG. 197.—COMPOSITE PEDIMENT-SURFACE DUE TO TWO STAGES OF GRADING.

many instances, but successive phases of grading may give a composite surface (Fig. 197), locally faintly convex.

The reader will note that while rock-fans appear at first sight as a curious and unfamiliar conception, in reality they provide another instance of the evident fact that the forms respectively cut and built by running water are morphologically comparable, though not indistinguishable. Thus a flat river-plain seen from the distance may prove on inspection to be a graded rock-floor with or without a thin alluvial veneer, or an aggraded flood-plain built essentially of alluvium. Similarly, under arid conditions, water-erosion on the flank of an intermont basin may cut a rock-fan or build an alluvial-fan. Further, if Crickmay (p. 185) is right in his emphasis on lateral corrasion as the essential agent of planation in the late stages of the normal cycle, there appears a strong homology between the processes of humid and arid planation, as contended by

W. M. Davis. The homology resides, however, not in the retreat under weathering of mountain fronts and valley sides, but in the dominance of lateral corrasion in shaping the limiting flat forms in both cases.

South African arid landscapes.—With the findings of the American workers now before us we may return to the problem presented by the African Inselberge-landscapes, in which the plain form is strongly dominant. In general terms it is tempting to speculate on the possibility that the African case represents a further development of the processes and results seen in arid North America, due to longer continued aridity and greater tectonic stability. The relatively youthful condition of the American arid landscapes certainly owes something to the occurrence of important faulting movements at more than one date. By contrast, the great African plateau regions have been largely free from strongly localized movements for a long period. Passarge's "plains of Bechuana type" may thus conceivably represent broad flat confluent "panfans" modified by long-continued deflation. Such a conclusion cannot be vindicated without, at least, a general reconstruction of the denudation chronology of South Africa. We are led again to recognize the fact, emphasized elsewhere in these pages, that land-form problems cannot be solved by morphological methods alone; reference must be made to the stratigraphical history of the area. Recent work by Maufe and others on Rhodesia and South Africa, and by Veatch in the Congo Basin tells against the assumption of an essentially arid origin for the chief plain surface of the regions in question.

The last major episode of sedimentation in Africa, south of the equator, was the accumulation of the great Karroo system, dominantly continental in character, ranging in age from Permo-Carboniferous to Jurassic. The basal Karroo beds rest on a surface locally moulded by ice, but, generally speaking, showing an irregular topography diversified by hills and valleys. Locally, as for example, north of Bulawayo, and possibly in the Kuruman Hills of Bechuanaland and the Langebergen, the pre-Karroo hills have been exhumed and form elements in the present landscape. Towards the end of the Karroo episode arid conditions prevailed, but these, like the similar conditions of the Trias in Europe, can have little bearing on the form of the South African land-surface. The best marked surface of planation widely traceable in Africa, and termed

by Maufe the pre-Kalahari peneplain, is a later feature cut indifferently across Karroo and pre-Karroo rocks. In the opinion of Maufe it marks the end of a cycle of erosion initiated by uplift and a return to humid conditions, sometime after the arid phase of the higher Karroo beds. This surface is well preserved in the high veld of Southern Rhodesia, and is traceable thence into Northern Rhodesia, Katanga, and perhaps even farther north. The high veld peneplain of the Southern Transvaal is probably the same feature, linked with the Southern Rhodesian development by the high ground in Bechuanaland. The surface appears to pass westwards beneath the deposits of the Kalahari region and emerges again from beneath these same deposits in parts of South-west Africa. Since the upper part of the Kalahari beds is of desert formation it might appear that the surface was of arid fashioning. In fact, however, the earliest deposits which rest on the pre-Kalahari surface in the Kalahari region itself are fluviatile, and in the mid-Zambesi basin and at various other localities extending to the equator, and perhaps beyond it, the lowest deposit is a fossiliferous siliceous limestone which must have originated under marsh—or "fluvio-lacustrine"—conditions.

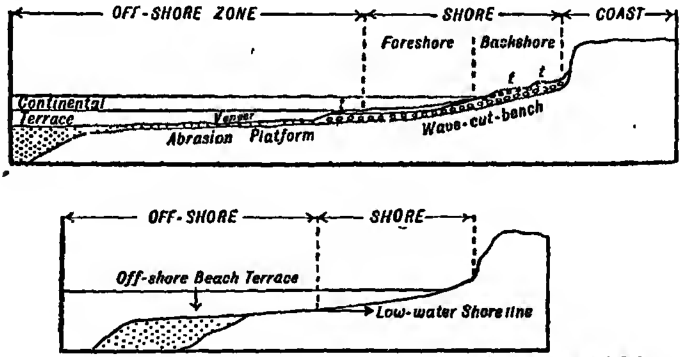
These facts support Maufe's inference that the surface was fashioned, or at least finished, under the control of humid conditions over a large part of its area. It was at a later date (probably late Tertiary), that the red Kalahari sands extended widely in South Africa. They appear to represent an "erg phase" which, since it is traceable from the Orange Free State to the Belgian Congo and over a breadth of some 16° of longitude, was much more extensive than the present Kalahari desert. This wide extension of desert sands appears to represent a migration, over a long period, of the tropical desert belt, of which, however, the details cannot yet be worked out. The vital point is that over large areas the desert sands are insulated from the pre-Kalahari surface by "humid" deposits, and hence cannot be regarded as directly related to that surface. Some parts of the surface must presumably have been fashioned under continuous arid conditions, for during the vast Jurassic–late Tertiary interval, the Tropical Desert Belt, though perhaps oscillating about a mean position, may never have withdrawn from certain areas. This was essentially the condition envisaged by Passarge and, while it does not apply to most of the regions studied by Maufe, it may well prove applicable elsewhere.

We are thus led, tentatively, to regard the great pre-Kalahari peneplain, not unfairly suggested by Maufe to be probably the largest feature of its kind in the world, as fashioned dominantly under humid conditions, but perhaps locally bearing the impress of long-continued arid erosion. Its present attitude reflects later episodes in the history of Africa, notably a general uplift of the continental margins. Since the "erg phase" of late Tertiary times, humid conditions have re-established river-action over much of the area, and from the earliest river deposits, of this, the current cycle of erosion, evidence of Palæolithic man has been obtained. This affords an upper stratigraphical limit to the vast period whose history we have briefly sketched, but other details of dating are at present obscure.

CHAPTER XXI

MARINE EROSION AND SHORELINES

THE erosive work performed by the sea is often more obvious and spectacular than that of rivers, and up to a point more readily understood. The systematic and quantitative study of the subject is of great practical importance in marine civil engineering, and much of the original work bearing upon it has been performed by engineers. In recent years the accumulated data have been successfully applied by geomorphologists to the problems of shoreline development, and it is now possible to recognize a cycle of marine erosion comparable and concurrent with the cycle of sub-aerial erosion.



[After Johnson, modified.

FIG. 198.—THE NOMENCLATURE OF THE SHORE-ZONES.
t, beach terraces.

Terminology.—The descriptive terminology of the " coast " or " shore " is in a state of some confusion, owing to the fact that the various terms have legal and colloquial, as well as scientific, connotations. In the present account we shall adopt, with minor exceptions, the terminology proposed by D. W. Johnson.

The term " coast " is reserved for the land-zone immediately behind the cliffs, while " coastline " is to be read as cliff-line or its equivalent, the margin of the land (Fig. 198). The " shore " is defined as the *zone* extending from low-water to the base of the cliff (Fig. 198). Over this zone the

water-line migrates and various actual shorelines can be distinguished—*e.g.* low-water and high-water shorelines, and again those of spring and neap tides.[1] There is a " normal " high-water shoreline corresponding with spring tides, but occasionally as at " equinoctial springs," at the peaks of other and longer tidal cycles, or when the water-level is raised by on-shore storm winds, the shoreline migrates further up the shore. We may thus distinguish the " foreshore," the region extending between the ordinary tidal limits, from the " backshore," lying immediately at the cliff-foot (Fig. 198). The extent of development of a well-marked backshore varies greatly from place to place. The region extending seaward of the low-water shoreline may be termed the " off-shore zone."

Within the zones, as thus delimited, distinctive features due to both erosion and deposition occur. The term ***beach*** is applied to debris temporarily accumulated in the shore zone. It rests on a wave-cut bench. It may be built seaward into the off-shore zone as an " off-shore beach terrace." [2] Similar terraces on the higher part of the beach may be called back-shore terraces. The wave-cut bench may terminate seaward in a steeper slope, representing part of the " initial surface " concealed beneath beach materials (Fig. 198). In other cases it is continued seaward in a flatter surface, the abrasion platform, over which a thin off-shore " veneer " of finer material may be spread. Further seaward, the off-shore sediments may thicken to form a " continental shore terrace " of which the upper surface, continued landward in that of the " veneer " or the abrasion platform, constitutes the " continental shelf."

Marine erosion.—Breaking wind-waves armed with rock fragments are the prime agents of marine erosion. The considered opinion of geologists and engineers now assigns only an auxiliary role to tidal or other currents, though they were formerly freely invoked in the explanation of shoreline features. Their chief work is the transport of the finer debris produced by wave-attack.

[1] The term " strand-line " is normally accepted as synonymous with shoreline.

[2] For " off-shore beach terrace " Johnson adopts the term " shoreface terrace," basing it on the conception of the " shoreface " of a delta as defined by Barrell. He thus introduces an additional zone—the shoreface, between the shore and the off-shore region. The term is useful if its definition be carefully borne in mind. It is not adopted here because of possible risk of confusion with " cliff-face." " Face " tends to suggest a vertical or steeply inclined rather than a sub-horizontal surface.

Wind-waves

In order to follow the erosive processes of wave-action it is necessary to appreciate the nature and genesis of wind-waves. A flat water-surface is initially thrown into small undulations by the friction against moving air but, once formed, the undulations can grow by the direct pressure of the wind against the sides of the wave-troughs. When directly wind-driven, the waves correspond to the "forced waves" of the physicist, but they may be transmitted beyond their area of origin for great distances as "free-waves" or "ground-swell." It is necessary clearly to realize that in deep water there is no progressive forward motion of the water particles in a wave. Each particle near the surface moves in a circular orbit, adjacent particles being in different stages of their circular course. On the crest of a wave they are moving forward; in a trough they are moving backward (Fig. 199). The reality of this

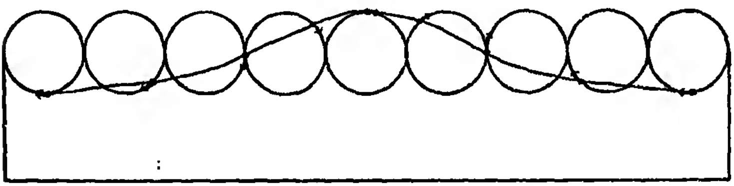
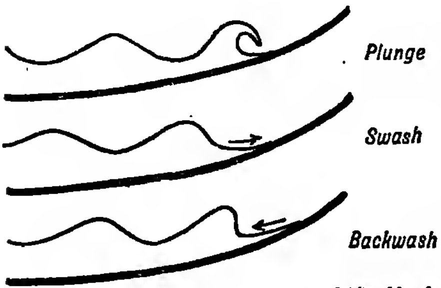


FIG. 199.—ORBITS OF PARTICLES IN WAVE-MOTION.

circular motion may be clearly appreciated by watching the behaviour of a floating object as a wave-crest and its succeeding trough pass under it. It is of the essence of wave-motion in open water that it is the shape or fold in the surface—not the water-mass itself—which moves on. The height of waves (measured from crest to trough) has often been exaggerated by casual observers, but it seems well established that heights of 50 feet occur in forced wind-waves, and a swell may attain a height of 20 to 30 feet. The wave-length, measured from crest to crest is normally not more than 600 to 700 feet in storm waves, though higher figures, up to 2,500 feet, are somewhat doubtfully recorded. In the open sea, wind-waves constitute but a superficial disturbance of the water. With increasing depth the circular orbits of the water particles become smaller, though in the same "phase" of movement as those vertically above them. At a depth equal to the wave-length all motion ceases.

Waves undergo important modifications as they pass into shallow water. They normally break when the depth of water (measured from the bottom of the troughs) is equal to their wave-length. The orbits of particles near the base of the wave are distorted by friction with the bottom, becoming oval or, in the limit, linear. The basal motion is retarded, while the top of the wave rides on, thus falling over forward and breaking (Fig. 200). Prior to the act of breaking there is a progressive steepening due to concurrent decrease of wave-length and increase of height. The forward rush of the water, leading to its piling up on shore, is in a wholly different category from the open water wave-motion; the water now has an onward motion in mass, and is a potential erosive agent. There is a compensating undertow capable of transporting fine rock-material seaward.



[After Marsh.

FIG. 200.—A BREAKING WAVE.

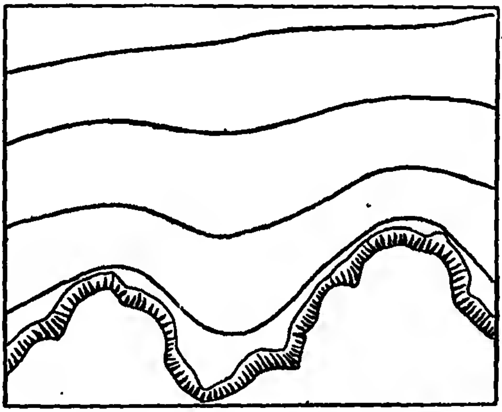
The line or "front" of a wave is also modified during its inshore journey. The shallow water off headlands or salients in the coast early arrests the forward progress, but the wave sweeps on into the bays for a greater distance before being checked. Thus the wave-front becomes bent or refracted (Fig. 201). In this way there is a tendency for the waves to advance normally, rather than obliquely, to the shore at all points, and there results a concentrated attack from both sides upon headlands, while the bays are relatively protected.[1] Nevertheless, it must be noted that oblique incidence of waves on a shore is a perfectly possible and usual circumstance, especially when they are strongly wind-driven. In such cases the "swash," or uprush, of the wave carries it obliquely up the shore slope, while the backwash descends normally in the direction of greatest slope.

The erosion performed by waves is largely, though not

[1] For this reason it is quite incorrect to suppose that a much indented coastline owes its existence to powerful wave-attack, hollowing out bays or gulfs. On the contrary, wave erosion tends to straighten the line of the coast. A high degree of indentation nearly always implies submergence of an irregular land-surface.

entirely, due to the rock fragments they carry. The direct blow of a mass of falling water may be equivalent to that of a weight of many tons and its shattering effect has been displayed on many exposed breakwaters. The alternate compression and expansion of air in cavities of a cliff face is an important auxiliary effect, leading to the wedging off, or " starting," of joint-bounded blocks from the face. But presented with a set of tools, ranging from immense boulders to fine sharp sand, wave-action, like river-action, can achieve a cumulative abrasive effect which exceeds that of its more direct attack.

It is obvious that effective wave-attack is somewhat severely restricted in vertical range. Its normal upper



[*After Davis.*

FIG. 201.—WAVE REFRACTION.

limit is set by the height reached by powerfully driven wind-waves at high-water. Its lower limit, the level termed " wave-base," below which the finest mud remains undisturbed by wave-agitation, is not readily fixed, and somewhat discrepant estimates of its position have been given. There is clear and abundant evidence that active abrasion may proceed at a depth of 100 feet below the surface, and there are good reasons for supposing that some disturbance can be produced by waves at a depth of as much as 600 feet—corresponding to the edge of the continental shelf, in many areas. However, the possible transport of fine sediment at greater depths does not bear directly upon the active erosion of the land-edge, which ceases upward a few feet above high-water and downward at a

somewhat greater, but variable distance below low-water. It thus results that wave-erosion operates like a gigantic saw of considerable, though limited, thickness applied near the base of the cliffs. Without the co-operation of rain-wash, gullying, and land-slips [1] the process of cliff recession would come virtually to a standstill, the waves cutting a horizontal notch along the base of the cliffs.

The Load

The "load" in marine erosion is partly self-supplied, but it receives accessions of river-borne debris brought down to the coast, and also of material falling from the cliff-face. It is necessary to consider the mode of its transport and disposal under wave-action. A portion of the load of waste generally forms deposits on the foreshore, ranging from shingle to sand and mud. Such deposits are essentially ephemeral, representing mere halts in a general process of transport. The beach at any place marks a local and temporary balance of supply over removal, and as such is comparable with the waste-mantle of a land-surface. Some shores are normally without beach deposits. In others they may persist for many years, until an increase in transporting energy during a succession of storms strips the foreshore bare, down to the wave-cut bench below.

Longshore Drifting

The normal fate of beach material is progressive comminution and ultimate removal either by "longshore" drifting or off-shore transport by undertow into deeper water. The magnitude of longshore drift has long been evident to harbour engineers, who have discovered to their cost that artificial interference may lead to complex and unexpected results. Folkestone Harbour was formerly cumbered by shingle drifting from the west. The extension of the western pier has arrested this, leading to an accumulation of shingle on its western side. The coast to leeward

[1] Landslips are common where cliffs are formed of clay or where beds of sand and clay dip seaward. The back of the slip is generally curvilinear and its "sole" approximates to semi-circular form. The detached portion of the cliff-top is thus tilted landwards, while there may be actual up-thrusting on the foreshore or beyond. Complicated structures of this type, due to repeated slipping, are exposed on the foreshore near Folkestone, Eastbourne, and at the toe of the great slipped "Undercliff" near Ventnor. The superficial portions of clay slips frequently descend as veritable "mud-glaciers" which protrude on the foreshore as small temporary capes.

has thus been starved of shingle and the depleted beach has failed to maintain its protective rampart, with resulting increased loss of land due to wave-attack. A similar artificial arrest of drifting shingle is often effected by groynes, on one side of which the shingle is piled up. The existence of far-travelled pebbles in a beach is a further index of coastal drift. It is a well-known fact that the quartzite pebbles of the Budleigh Salterton cliff have found their way eastwards into the beaches of Kent and Sussex and, though it is doubtful if this transport could take place in the existing condition of the coast, it remains a clear testimony to former drift. Longshore drift also displays its action in the building of spits (p. 335).

Attempts to account for longshore drift have invoked either tidal currents or breaking waves as the chief agent. Tidal currents off-shore rarely exceed a velocity of 2 or 3 knots. Though higher velocities occur in straits, inshore

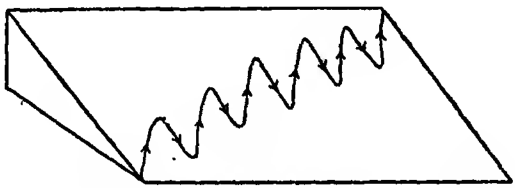
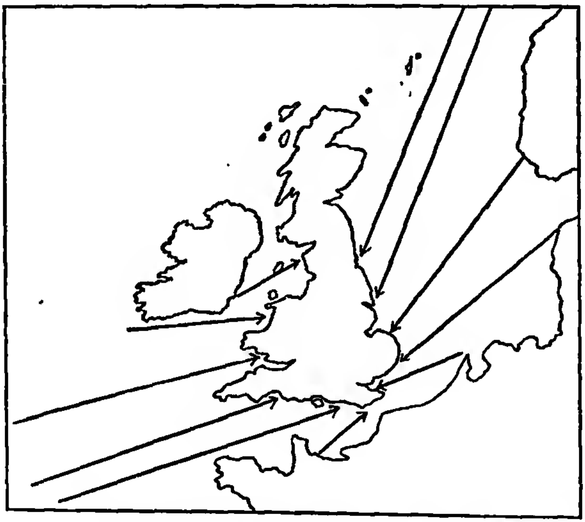


FIG. 202.—ZIGZAG TRANSIT OF BEACH MATERIAL UNDER THE INFLUENCE OF BREAKING WAVES.

the velocity is undoubtedly less than the figure quoted. Experimental work indicates definitely that such currents are incapable of transporting shingle in the mass, though they may carry finer sediment or roll isolated pebbles. Breaking waves are certainly more efficient in the transport of shingle. With waves impinging obliquely on the shore the swash (p. 324) has a longshore component, while the backwash is " normal." Transported material will thus pursue a zigzag path along the foreshore (Fig. 202). Since obliquely incident waves are wind-driven it might be supposed that on coasts with variable or seasonal winds there would be little or no resultant drift, but only an oscillation to and fro with the changing winds. On many coasts, however, a resultant drift in one direction or the other plainly exists. In explaining these resultant drifts we should naturally have recourse to data as to the frequency and force of winds from the various quarters.

Fetch

It has been found, moreover, that the " fetch," or length of water-surface over which the wind from any quarter blows, is also a most important determinant of wave-size and efficiency of transport. In other words, a wind of moderate force blowing across a wide stretch of water is capable of generating larger waves than a stronger wind with a small " fetch." Fig. 203 shows the directions of maximum fetch round the coasts of England. They are seen to be in agreement with the resultant drifts—eastward along the south coast, southwards along the east coast, and, on the whole, northwards along the west coast. It



[*After Marsh.*

FIG. 203.—DIRECTIONS OF MAXIMUM FETCH AROUND BRITAIN.

should be noted, however, that with a few exceptions the drift is also accordant with the direction of advance of the flood-tide on the several shores, so that the argument is not final. Nevertheless, in inland water bodies, such as Lake Michigan, where tidal currents are absent, longshore drifting takes place under the influence of wind-waves, and it is demonstrably largely controlled by the " fetch " factor (Fig. 204). Thus, though wave and tide may locally co-operate on the shore, the tidal current is not essential to the drifting. T. W. Marsh records a significant observation, and one of the very few which bear

directly on the problem. He says: "With the waves acting against the ebbing tide at Orfordness the writer has seen shingle being thrown southwards by the breaking waves, and sand in suspension being drifted northwards by the ebb." This serves to remind us that though tidal or other currents may be ineffective in moving shingle, they can and do transport the finer shore debris.

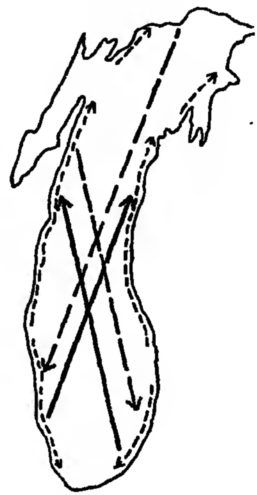


FIG. 204.—DIRECTIONS OF MAXIMUM FETCH AND OF BEACH-DRIFTING IN LAKE MICHIGAN.

The cycle of shore-erosion.—In studying the form of shores it proves possible to adopt the genetic mode of approach and terminology which we have employed in the study of normal erosion. A shore may be regarded as resulting from an initial form, erosion and deposition giving rise to a succession of secondary or sequential forms, the whole thus passing through the stages of youth, maturity, and old age. Some portions or traces of the initial form may persist until maturity is reached, after which all such traces are lost. The initial form may vary very widely. In all cases the first act in the evolution of a shore is a change in the relative position of land and sea, bringing the sea-margin against either land-surface or sea-bottom. In general we may distinguish two cases: (1) submergence of a land-area, involving a landward shift of the strand-line, and (2) emergence of a portion of sea-floor, giving a seaward movement of the strand-line. Such adjustments may result from uniform regional uplift or depression of the land, from differential warping, or from eustatic oscillations of sea-level.

The development of shore-profiles.—Let us, in the first instance, consider what is perhaps the simplest case, viz. that of the submergence of a land of fairly high and irregular relief. The water-level will then come to rest against the former hill-sides and the initial profile will show steep slopes descending into deep water. Waves will advance unchecked, directly on the shore, cutting a notch in the edge of the land and thus initiating a cliff.

The resulting debris will be disposed as a submarine talus below the zone of wave-movement (Fig. 205*a*). A continuance of this action, co-operating with gravity and subaerial wash and slip, will cause active recession of the cliff-face and the formation of a wave-cut bench and abrasion platform stretching seawards from its foot (Fig. 205*b*). The increasing load of debris will be added to the original

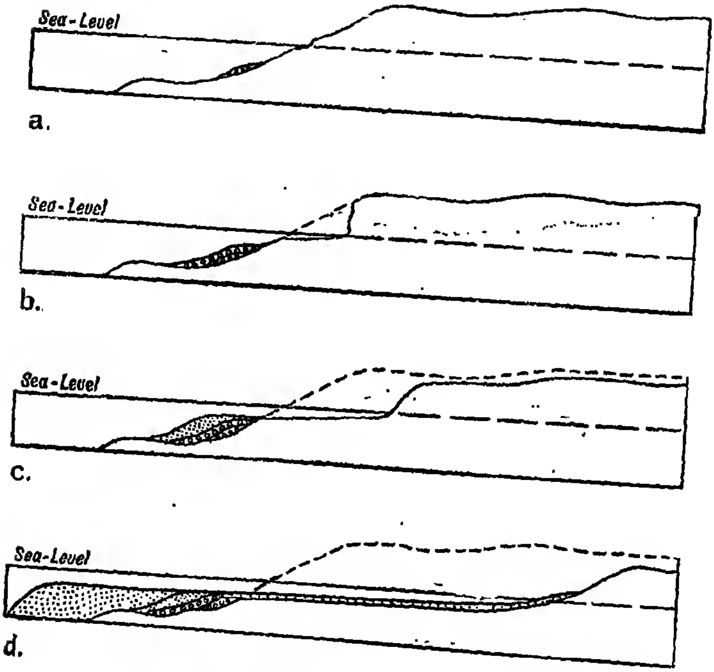


FIG. 205.—STAGES IN THE DEVELOPMENT OF A SHORE-PROFILE FOLLOWING SUBMERGENCE. [*After Johnson.*

(*a*) Initial stage. (*b*) and (*c*) Stages of youth. (*d*) Mature stage.

bank of submarine talus, extending its upper surface seawards. The state of affairs thus reached is strictly comparable with the youth of a stream valley. Wave energy is still high and the "load," though increasing as the cliff-height increases, is not sufficient to absorb all this energy; hence active wave-attack continues, causing recession of the cliff-foot as fast, or faster than, the retreat of the cliff-top. In pursuance of this analogy we may note.

further, that the youthful shore-profile will be diversified by irregularities due to differences in rock-hardness. A consideration of the course of normal erosion guides us in the deductive treatment of the shore-cycle. We shall expect a progressive equation of energy to load, tending to a state of equilibrium. There will obviously be a loss of wave power, as the obstructing shore bench widens, and concurrently an increase of load as the cliff-height increases. The erosive attack of the waves will therefore decrease, and the cliff-top will recede faster than the base (Fig. 205*c*). The sloping of the vertical cliff is thus precisely comparable with the process of valley widening (p. 154). The on-coming of this phase will take time, and during this period the general land level will be lowered, and some lowering of the abrasion platform will also take place in the course of the transit of debris across it. When finally a balance is struck between the work to be done and the energy available to do it, maturity is reached. The profile of the shore, *i.e.* the combined profile of cliff, wave-cut bench, abrasion platform (with or without sedimentary veneer), and off-shore sediments, is then analogous in its significance to the graded profile of a mature river. At every point the slope has the required steepness to permit the available wave-energy to remove the load presented to it. It is steep inshore, where the debris is coarse, and flattens progressively seawards. The precise profile of equilibrium can, of course, vary widely according to the nature of the rocks eroded and the physiographic and climatic setting of the coast. Moreover, as in a stream, the equilibrium is approximate only, being rather an oscillation on either side of an ideal state. Waves from different quarters and of different sizes each tend to produce their appropriate equilibrium profile, but the resultant profile will approximate most closely to that formed at intervals by large storm waves, which, like the floods of a river, can effect more change in a few hours than fine weather ground-swell can produce in a year.

Apart from the general form of the mature profile a significant feature is the great seaward extension of the off-shore beach-terrace, and its overlap on to the abrasion platform as a relatively thin veneer of debris in a state of intermittent transit (Fig. 205*d*). As already noted, it marks the excess of sediment over the quantity which the waves can transport, and is liable to periodical complete removal. The surface of the beach itself, continued seawards in the

off-shore beach-terrace, is part of the shore-profile of equilibrium, being slightly concave upwards. It forms the least stable part of the profile, being subject to comparatively sudden changes under the varying incidence of wave-attack. If, at any period, the beach-profile becomes too steep for equilibrium the gradient is lowered by forward building or *progradation*, whereby successive "beach ridges" (see p. 340) are added to the growing structure. Conversely, the steepening of the profile by cutting away at the breaker line is *retrogradation*. Progradation and retrogradation frequently occur in alternating short periods; but a shore may show evidence of the dominance of one or the other process, tending, as a whole, to be built forward or cut back over a longer period. The two processes are evidently analogous to aggradation and degradation in the case of a river. We shall note in more detail below the precise manner in which the effects are achieved (p. 339). For the present we may note that both terms cover a wider range of processes than those concerned in the construction and demolition of beaches. Progradation may result from the extensive deposition of river alluvium, as in deltas, and retrogradation comprises not only beach recession but the general recession of the coastline under wave-attack.

Little need be said concerning the old age of a shore. The passage from maturity to old age will be marked by further recession and sloping of the cliff until it becomes hardly recognizable, and further extension of the blanket of sediments whose growth started as a simple terrace. In the limit the entire land-mass would be reduced to wave-base. The conception is largely of theoretical value and certainly corresponds to no state of affairs which is at all frequently realized. Clearly the completion of the marine cycle requires an immense period of "still-stand," and granted such a period it has been held by many that the lowering of the land by fluvial agency would be complete under normal conditions long before the marine cycle could run its course unaided. It must be remembered that the localized "saw cut" of marine erosion is competing with the more effective "sand-paper and file" action of wind and water, applied generally all over the land-surface. Moreover, the slightest interruption due to uplift of the land, say, to the extent of 6 to 10 feet only, condemns marine erosion to what is virtually a fresh start, while it does not hinder but slightly accelerates river-erosion. Thus,

although the existence of many wide abrasion benches, both at and above the present sea-level attests the reality of marine planation, it is probably less effective than sub-aerial peneplanation (cf. p. 185). A condition which favours extended marine planation is steady subsidence, allowing wave-attack to proceed at constantly higher levels on the land-mass. Such a condition must have been realized during the great marine transgressions ; but even in such cases it is likely that marine planation merely finished or trimmed the work of normal peneplanation.

Let us now turn to the second case, *i.e.* when the initial act of shore evolution is one of emergence, bringing the water-surface against a gently sloping sea-bottom. The initial profile will, in such case, commonly be less steep than that necessary for equilibrium. The steepening of the profile involves erosion off-shore and deposition near the coast, resulting in the formation of an off-shore bar (p. 346). The seaward side of the bar will develop the normal beach-profile of equilibrium. Concurrent wave-attack on the inner coast will develop low cliffs and a small abrasion platform, etc. The lagoon between the bar and the inner shore will tend to become silted up with tidal or river-borne sediment, and, assisted by the activity of certain salt-water plants which entangle the drifting mud, may be built up into salt-marsh, over part of the surface of which sand-dunes may form.

The building of the off-shore bar is in reality an act of progradation and further local and temporary progradation may follow. In the long run, however, the bar is subject to inevitable retrogradation, being driven landward under wave-attack. It advances across the salt-marsh deposits, which are destroyed in the retrogradation. When it reaches the initial inner shore, maturity may be said to have been reached. During its landward migration the off-shore profile will, of course, have developed, the wave-cut bench and terrace (if any) being gradually lowered. The later stages of evolution in profile will not differ materially from those of a shoreline of submergent type.

Constructional forms of a developing shore.—We have briefly indicated the sequential stages in profile which succeed one another in a developing shore. It is clear that there is also an evolution in plan, worthy of separate

consideration. Before we outline this evolution in general terms, we must devote attention to the constructional forms, generally of the nature of embankments projecting above water-level, which diversify the plan of shores during certain parts of the cycle.

The consideration of this topic brings us face to face with the great extent of our ignorance with regard to the precise mode of operation of wave- and current-action. The patient and acute observations of Gilbert, Davis, Johnson, and others in America, and of such workers as Cornish, Owens, Steers, and Lewis in Britain, have cleared part of the obscurity as to *processes* in the case of certain limited areas. In general, however, it is only the

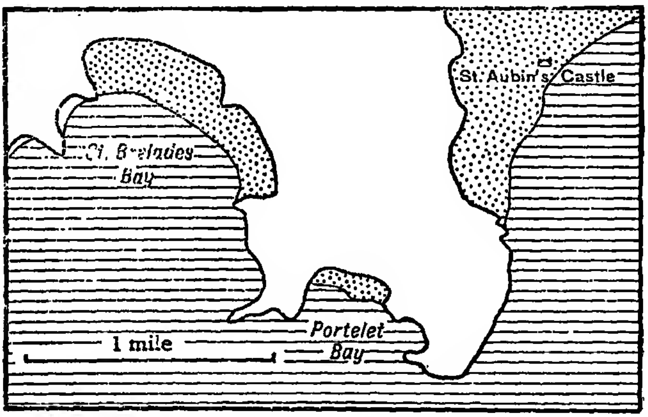


FIG. 206.—BAY-HEAD BEACHES IN S.W. JERSEY.

results which we can see and measure, and we may therefore begin with a short descriptive account of the constructional forms of the shore. By study and comparison of such forms a limited ground of assured fact can be gained. Further progress depends on direct study of the processes.

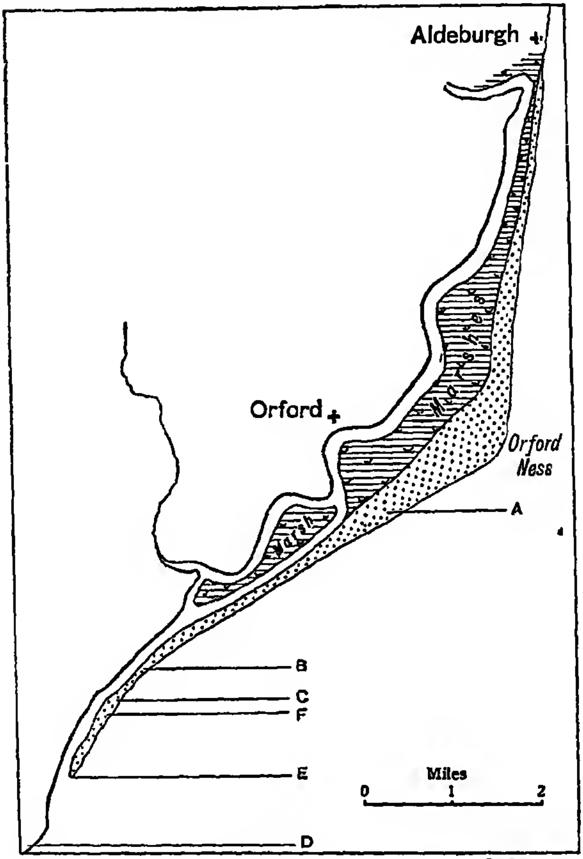
On a retrograding coast characteristic beach-forms are short-lived, being destroyed almost as fast as they are formed. Under other conditions semi-permanent embankments arise. When they emerge above sea-level their seaward face tends to assume a profile of equilibrium under wave-attack, while their landward face, if any, covered by quieter water, approximates to the sub-aqueous angle of rest of the material. The commonest forms of accumulation are " bay-head " or " pocket " beaches, which extend for varying distances round the sides of bays, and even

become continuous with " headland beaches " if the supply of material is general and copious (Fig. 206). Bay-head beaches tend to arise where the undulations of the shore in plan are open and gentle. With sharper bends in the shoreline, spits, tangent to the shoreline, are more characteristic ; these tend to short circuit the narrower inlets.

The growth of spits.—Without making any assumption at all as to the precise manner of building, it may readily be demonstrated that spits grow or contract lengthwise. The distal ends of many spits have fluctuated in position during recent historic times, affecting the access to estuaries and harbours. Study of old maps reveals even more clearly the fact of lengthwise growth, though possible cartographic inaccuracies must be allowed for. Such growth is not steady and progressive, but spasmodic, alternating with phases of retreat. Steers, in a study of the great spit which deflects the mouth of the River Alde near Orford, finds evidence that at the date of founding of Orford Castle (1165), the distal end of the spit was near A on the map (Fig. 207). Later records are in some degree conflicting, but leave little doubt that the distal point was near B in Elizabethan times, and that it advanced to near C during the eighteenth century. The first edition of the Ordnance Survey One Inch Map (1805), shows further progression. By the end of the century the spit had extended to the latitude of Shingle Street (D on the map). Thereafter a reverse movement set in : Fig. 207 shows the position of the point in 1902, while in 1923 it reached the neighbourhood of F. In the latest phase, southward advance appears to have been resumed. The total growth for the 700 years ending in 1897 was 5½ miles, representing an average annual addition of 13 or 14 yards.

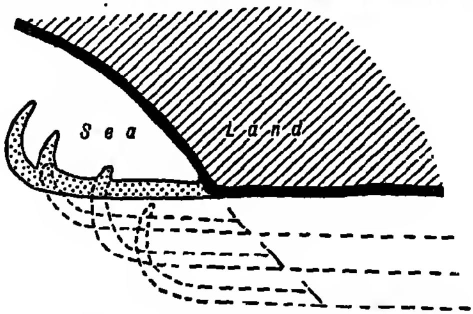
The distal end of a spit is often curved inshore. In " compound spits " minor ridges, or " laterals," may branch from the landward side. The conditions under which these arise are sometimes difficult to reconstruct ; but in some cases, at least, they may be explained on the assumption that the spit as a whole moves landward incidentally to general coastal recession, so that laterals mark recurved terminations of the spit in a succession of former seaward positions (Fig. 208).

Continued lengthwise growth may convert a spit into a *bay-bar* (Fig. 209). A similar effect might clearly arise from the opposed or convergent growth of two spits.



[After Steers.

FIG. 207.—GROWTH STAGES OF THE ORFORD SPIT.



[After Johnson.

FIG. 208.—A COMPOUND RECURVED SPIT.

Islands often show spits trailing landward from their ends. These may join, forming a *looped bar* (Fig. 210*a*), or connect with the mainland, forming island-ties, or *tombolos* (Fig. 210*b*).

A change in direction of spit growth or convergence off-shore of two independent spits gives rise to cuspate bars, of which the looped bars of islands are a special type. Progradation of such cuspate bars converts them into *cuspate forelands* typified by such features as Dungeness, Cape Canaveral on the Atlantic coast of Florida, and the Darss in Pomerania. Such forelands are often, in essence, compound spits preserving an area of marshland behind them.

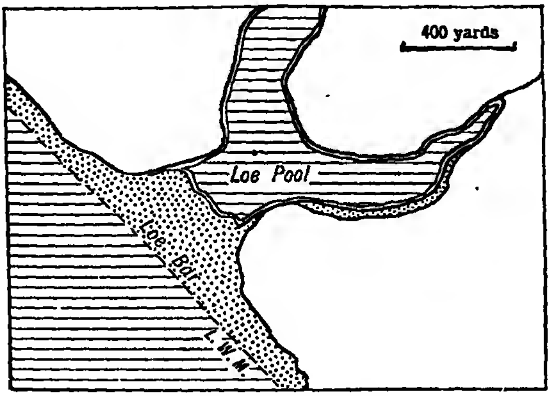


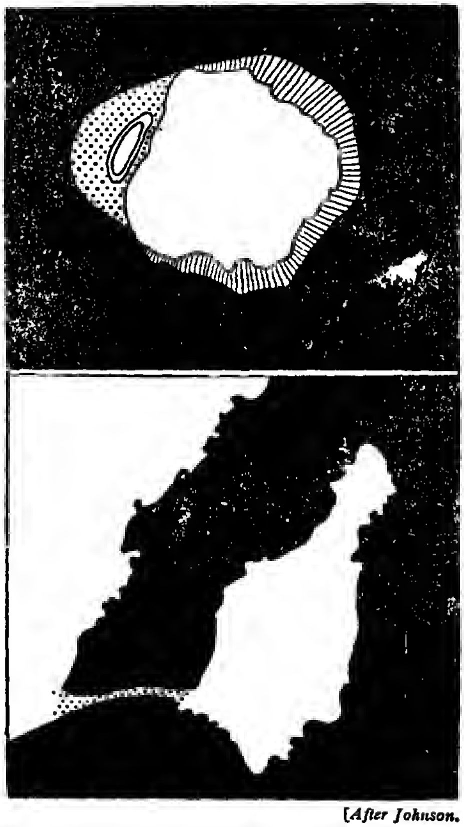
FIG. 209.—LOE POOL.
A bay-bar in South Cornwall.

From a comparative survey of such features we learn that they show well-marked lengthwise growth, are subject to recurving and apparent branching. A suggestion is also conveyed that they may advance landward as a whole, and it is also clear that they may be built forward by additions to their seaward face. How are these results achieved ? Most explanations of these structures assign an important role to longshore drift, and the first question at issue is the nature of this drift. Many have spoken definitely of a longshore current, and have implied that the genesis of this current is to be sought in the tidal ebb and flow. We have seen that opinion has set definitely against this view in late years. In the first place, the inshore velocity of the tidal currents is demonstrably insufficient to transport shingle, whereas transport of

shingle by obliquely breaking waves has been fully demonstrated. To the significant observation of Marsh, quoted on p. 329, we may add that of Lewis, who noted that a swift ebb current (4 to 5 knots at the surface) off the Hurst Castle Spit in the Solent was unable to disturb light shelly material at the bottom (where its velocity

a

b



[*After Johnson.*

FIG. 210.—LOOPED BAR AND TOMBOLO.

(*a*) Looped Bar, Shapka Island, Alaska (after Johnson). (*b*) Tombolo linking Marble Head Island (Mass.) with the mainland.

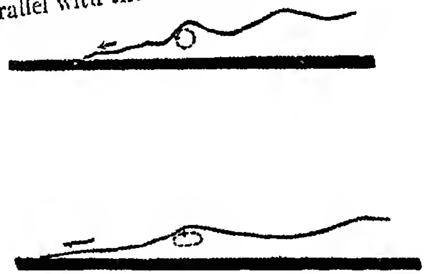
would be less), but that such a current increased the size and obliquity of waves travelling in the opposite direction. Further arguments are to hand. In some regions wave drift and tidal advance are in the same direction, and we are thus left in doubt as to their relative efficacy. In others, spit growth proceeds in a direction opposed to that

of the main tidal current, while it agrees with the direction of prevailing wave drifting as directly observed, or deduced from records of the prevalent winds or " maximum fetch." Finally, it is clear that shore embankments can grow in lakes where wave-action is in progress, but tidal currents are not operative. We are thus assured that wave-action alone can produce shore embankments, and we may accordingly adopt, as a reasonable working hypothesis, the view that it is a major factor in all cases. Nevertheless, our present knowledge does not justify us in assuming that all other agents are impotent. The extent to which tidal ebb and flow can, in special circumstances, co-operate with or retard the action of waves or produce similar effects unaided is yet far from certain.

If we are right in assuming that the growth of spits and kindred structures is maintained by debris transported by longshore drift in the zone of breaking waves, it is none the less evident that this process is not, in itself, sufficient to explain their origin. Longshore drift accounts for the *supply* of debris, and it should be noted that the opening of tidal or river breaches in an embankment—a frequent phenomenon—arrests the continuous chain of supply, depriving the leeward portions of the bank of much of the substance for continued growth. But longshore drift cannot begin to act until actual emergence occurs, and we must thus envisage at least two other processes : (*a*) the building up of the embankment to water-level ; and (*b*) the further stages of building after it has emerged. Concerning the former we are reduced to surmise, since direct observation is difficult ; but the latter is more amenable to study. As long ago as 1834 Palmer distinguished between the destructive and constructive phases of wave-action, noting that waves of high-frequency commonly break on the backwash of their predecessors, so that there is almost continuous seaward motion of the waters in contact with the beach, leading to destruction by " combing down." Lewis has recently extended the inquiry, noting that the frequency of waves affects their form and erosive action. With high frequency waves the swash is weak, owing to the relatively short wave-length and nearly circular orbital motion of the waves (Fig. 211), in virtue of which they plunge steeply on breaking, imparting little horizontal impulse to the swash. Backwash is thus unimpeded and " combing down " results.. On the other hand, low frequency waves

of longer wave-length show an "orbital form" of elliptical character (Fig. 211), and a strong horizontal component thus results in the swash. Such waves, breaking at the rate of six to eight per minute, have been observed by Lewis to push shingle up the beach and to build small beach ridges at the limit of the swash at all states of the tide.

Beach ridges.—It is agreed by all students of the subject that the stages of growth of many complex spits and forelands are marked by "beach ridges." These are often continuous for long distances and are known as "fulls," being separated by shallow hollows known as "swales" or "slashes." Thus, in the shingle foreland known as the Crumbles, near Eastbourne, there are some 60 fulls roughly parallel with the shore east of Langney Point, but



[*After Lewis.*

FIG. 211.—DESTRUCTIVE (*above*) AND CONSTRUCTIVE WAVES (*below*).

truncated by the shore west of that point. Processes akin to those described by Lewis have clearly been at work in producing such ridges. Some have sought to read lunar or climatic cycles into the regular succession of fulls, but the facts rarely, if ever, fit such an interpretation, nor should we expect regular growth. On the face of a developing beach there must be continual making and breaking of beach ridges with variations in the types of waves. Small ridges made at periods of neap tides must generally be demolished in the following "springs," and permanent accretion can only occur in special circumstances and at long intervals. An exceptionally long and well-developed phase of "quiet" constructive waves may build a ridge which survives subsequent demolition, but in general it cannot be doubted that major storms are accountable for the main ridges. This may seem a para-

doxical conclusion, since storm-waves, in the nature of the case, must be of generally high frequency and destructive character. Nevertheless, at high water large storm-waves not only " comb-down " large quantities of shingle from the seaward face of the beach, but build a rampart with part of the dislodged material at the top of the slope. Judged by their effects they are at one and the same time both constructive and destructive. Normal phases of construction and destruction alternate and largely destroy each other's handiwork, but high level storm beaches survive as permanent additions to the growing bank. The ridge built on Chesil Beach by the great storm of 1852 is still plainly traceable. It should be noted that a modification of the same action is responsible for the steady landward migration of narrow bars and spits. Material dislodged by storm-waves is thrown over the top, so as to extend the bank on its landward side at the expense of seaward wastage.

We arrive thus at the conclusion that while longshore drift provides the material for building, the building itself results from spasmodic progradation, by " frontal " wave accretion, in part, at least, at the time of major storms.

We still have to account for the directions taken by beach-ridges and the embankments of which they form part. In the case of normal spits (Fig. 208) it has frequently been implied by believers in a longshore current, that the latter slightly overruns the end of the spit, thus causing it, initially, to continue the line of the shore to which it is tangent—and, in general, carrying on its previous direction of growth, subject to the recurving tendencies of waves or currents crossing its end as it passes into deeper water. Clearly, this explanation cannot apply on the hypothesis that longshore drift is due to wave-action, for the drift automatically ceases where the spit ceases and cannot, so far as we know, achieve any sort of " overrun " effect. On the " wave hypothesis " prolongation of a spit is attributed to accumulation of debris near the end of the spit by longshore drifting, tending thus to shallow the water and afford scope for " frontal " building by breaking waves. If this is so we should expect the direction of the spit, and the beaches which build it, to be related to the building waves. A certain amount of confirmation of such a process is to hand. Thus, certain spits leave the shore at an angle where there is no point of

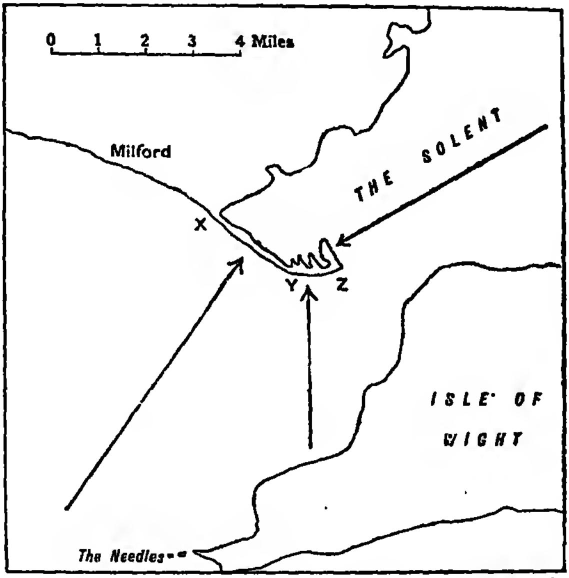
deflexion in the shoreline.[1] Here some explanation other than the over-running of longshore drift is plainly required. Moreover, though breaking waves build beach ramparts most effectively when they advance normally on the shore, Lewis has described instances in which obliquely incident waves appear to have built small beaches of their own, parallel with their fronts. Further, there is some evidence that large oblique storm-waves tend to slew round pre-existing beaches into parallelism with their front. In general, it appears probable that the shore-line direction, where forms of accumulation are concerned, tends to set itself normal to the direction of dominant storm-waves. These will not necessarily advance from the same direction as the prevalent waves responsible for resultant longshore drift. The latter will, in part, reflect prevalent wind direction, but the former will travel from the direction of the "maximum fetch." Over a period of years storm-winds will blow from all quarters, but the most powerful waves will arrive from the direction of the greatest stretch of water, and leave the most permanent legacy in building beach ridges and determining their trend.

Hurst Castle Spit.—Lewis has applied these principles in a tentative interpretation of the origin and growth of the Hurst Castle Spit, at the western end of the Solent (Fig. 212). It "takes off" at the eastern end of Christchurch Bay, where the main shoreline changes direction by nearly a right-angle. After continuing the direction of the windward coast for a short distance the spit bends so as to set itself nearly north-west to south-east. This portion is regarded as having been built up by dominant waves from the south-west. After a run of over a mile in this direction the seaward face turns to an east to west direction. Laterals spring from the back of this portion, trending about north-north-west to south-south-east, and beyond Hurst Castle the outer shoreline swings round the point so as to join the last of these laterals.

The first change of direction at Y (Fig. 212) is interpreted as follows. South-easterly growth became slower with progress into deeper water, and south-westerly waves were here too strong to build a rampart which could resist their own attack. The off-shore accumulation

[1] This is true, for instance, of the embankments which form the bases of Blakeney Point and Scolt Head Island on the north coast of Norfolk. It should be noted, however, that Steers is inclined to regard these embankments not as true spits, but rather in the nature of off-shore bars (p. 346), which have been driven inshore.

of shingle near the distal end afforded opportunity, however, for southerly storm-waves, weaker than the south-westerly set, to engage in beach building. It should be noted that since the prevalent waves responsible for longshore drift come from the south-west, they impinge much more obliquely on the section YZ than on XY. Once the corner at Y was turned, therefore, the rate of supply of material would increase and extension could proceed readily when suitable building waves occurred. During this stage, however,



[*After Lewis.*

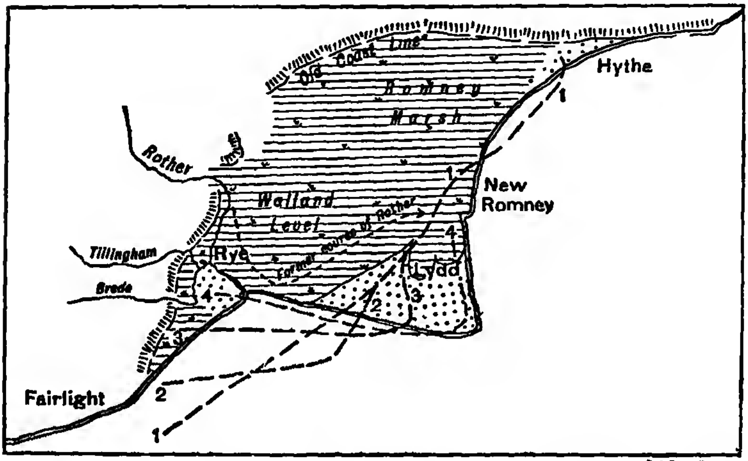
FIG. 212.—HURST CASTLE SPIT.
The arrows show the directions of advance of building waves.

the laterals also grew. They reflect, in the opinion of Lewis, the periodic influence of dominant north-easterly waves coming down the Solent. At any given stage there would be an off-shore accumulation of shingle around the point. This was available either for continued easterly growth under the influence of southerly waves, or for the building of acutely inclined laterals by north-easterly waves. The two tendencies have alternated under the long-period vagaries of wind and weather. At present a slight tendency to eastward prolongation is manifest.

Dungeness.—Cuspate forelands of the type of Dungeness are in many cases complex spits showing frontal extension by progradation. It was formerly customary to suppose that they marked the meeting place of opposed tidal currents, with associated " eddy currents," and that they grew in the triangular area of " slack water " left where the opposed currents turned off-shore. Such an origin was plausible in the sense that it was readily envisaged in vague terms, but, as we have seen, there is as yet little evidence of the existence of such currents, able to transport coarse debris. Dungeness has been claimed by many writers as marking the meeting-place of the North Sea and English Channel branches of the British tide. In fact, however, there is no one meeting place of these tides ; the point of opposition varies over a considerable area. Moreover, any such explanation of Dungeness must inevitably be embarrassed by the presence of the similar foreland of Langney Point, some twenty-five miles to the west. In view of the evident analogy between certain features of Dungeness and those of complex spits of the Hurst Castle type, an hypothesis involving wave-building appears to be strongly indicated and has been elaborated in some detail by Lewis.

Dungeness lies approximately midway between the cliffs of Fairlight and Hythe. It occupies part of the seaward edge of a former bay, which, concurrently with the formation of the outer shoreline, became filled up by natural silting and artificial reclamation to form the great expanse of Romney Marsh and Walland Level. Lewis supposes that at an early stage a complex spit started to grow eastwards from a point, south of the present coast at Fairlight. The growth of this spit was aided by a general elevation of the land or drop in sea-level, so that it ultimately extended past Lydd and New Romney to the neighbourhood of Hythe, becoming virtually a bay-bar (Fig. 213). It is possible that the River Rother crossed the present marsh area to an outlet near Hythe. Thereafter, wave breaches were formed near Fairlight and New Romney, probably aided by a rising sea-level. The New Romney breach gave exit to the Rother, while the Fairlight breach came to serve as outlet for the waters of the Tillingham and Brede rivers. The latter river-outlet cut off the shoreline lying eastward from shingle supplies from the west. As a result wave-action was able progressively to slew the impoverished shoreline round to

a more nearly east to west direction, roughly normal to the direction of advance of the dominant storm-waves.[1] Thus was created the point of deflexion in the shoreline which, with further development, became the Ness. The southward-facing edge was driven backwards, sharpening the point. Towards the point, shingle was carried by longshore drift from the west. Beyond the point, this drift naturally slackened, and Lewis is of opinion that shingle of westerly provenance was built into lateral ridges



[After Lewis.

FIG. 213.—STAGES IN THE DEVELOPMENT OF DUNGENESS.

by dominant waves from the east. Such an action may still be studied under favourable conditions at the present point, and it is reasonable to assume that it was primarily responsible for the eastward shift of the Ness from its initial position (Fig. 213). Lewis, therefore, gives as the reason for the form of Dungeness, the sudden change in exposure at the point ; large waves approach either from the south or the east so that the two shores face these directions. The sharpness of the point is due to the proximity of the French coast preventing the occurrence of large waves from a south-easterly direction.

[1] On this view the Ness was essentially initiated by shingle trapped between the Fairlight and New Romney breaches. The period of elevation leading to the "bay-bar" stage is identified with the "Submerged Forest period" (p 421) The wave-breaches were formed and the river exits well established by Roman times. A further breaching of the shoreline leading to the destruction of Old Winchelsea and the southward diversion of the Rother occurred in 1287. This cut off Dungeness from the shingle mass south of Rye, which may retain traces of early stages of spit growth.

This particular example may foreshadow a general principle, viz. that cuspate spits and forelands depend upon a sudden change of exposure, allowing large waves to approach from two directions oblique to the shore, but never directly on-shore. Such a condition is obviously likely to arise in "narrow seas" and elongated lakes. It may not be so readily applicable to forelands, such as Cape Canaveral in Florida and the Darss in Pomerania, which occur on open coasts.

Off-shore bars.—We come, lastly, to the case of off-shore bars, concerning the origin of which there has been wide difference of opinion. There is no reason to doubt that wave processes, analogous to those described above, are responsible for the "up-building" of such bars, both below and above water-level, but the source of the material for building is open to question. Davis, following de Beaumont and Shaler, regarded the material as derived by wave-erosion from the off-shore bottom. Gilbert, on the other hand, attributed the main supply to longshore drift in the zone of off-shore breakers. It is evident that such action must take place once the bar has emerged, but, as in the case of spits, it is difficult to envisage the initiation of the bar by such means. The two cases, however, should be distinguishable by study of the off-shore bottom profile. If off-shore bottom erosion were absent, the bar should rise as a simple additive feature above the unmodified sea-floor, which, in the case of a youthful emergent shoreline, should continue the slope of the coastal plain, or in other words, intersect the water-surface near the main shoreline (Fig. 214). Off-shore erosion should produce a flatter profile in front of the bar, and if projected, it should reach sea-level landward of the coast (Fig. 214). The researches of Miss B. M. Merrill (reported by D. W. Johnson) upon examples from the American, Dutch, German and Italian coasts showed results generally accordant with the latter condition. While, therefore, the co-operation of longshore drift need not be excluded, the conclusion of Davis that off-shore bars "might be developed essentially under the

FIG 214.—THEORIES OF FORMATION OF AN OFF-SHORE BAR.
(a) Without off-shore erosion.
(b) With off-shore erosion.

control of on- and off-shore action alone" appears to be sound. The great bulk and extent of some off-shore bars, demanding copious supplies for building, supports this hypothesis.

We may remark, further, that such sub-aqueous building by on-shore "wave-drive" appears to be an essential process in initiating many, if not all, embankment structures both on-shore and off-shore. As already noted, we know little of its precise mechanism, yet some such process is clearly at work. Elongated embankments, completely submerged, exist in many off-shore tracts, as off the mouth of the Thames. In explaining such structures there arise at least four available hypotheses. The banks may be due to (*a*) differential wave or current scour; (*b*) differential sedimentation, comparable with the process which gives the off-shore "fingers" of a delta; (*c*) submergence of structures formerly built to, or above, water-level in in-shore waters; (*d*) sub-aqueous wave-building redistributing a uniform sheet of sediment. Any of these hypotheses may be found applicable in individual cases, but, for many, the last alone appears to suffice.

It should be noted that since off-shore bars inevitably travel landwards under wave-attack during general coastal recession (p. 333) they may come to occupy the position of bay-bars, spits, tombolos, etc., and become virtually indistinguishable from them. This alternative possibility should always be kept in mind when considering the origin of in-shore embankments. Thus, the basal structures of Blakeney Point and Scolt Head Island on the Norfolk coast may be regarded as spits springing initially from the shoreline, or remains of an off-shore bar driven landward (footnote, p. 342).

In accordance with recent opinion, the foregoing discussion has placed emphasis on wave-action, and for structures in which shingle bulks largely we have yet to find evidence of any other efficient process. There are, however, embankments formed of finer material, such as currents can transport, and for these, at least, the possibility of current-building should be kept open as a working hypothesis. Our knowledge does not yet justify dogmatism as to what is, or is not, possible in the complex processes which mould a developing shore.

The evolution of shores in plan.—We are now in a position

to obtain a general view of the evolution of shorelines in plan, taking account of both wave-erosion and wave-building. The simplest and most striking series of sequential forms arises in the case of the submergence of

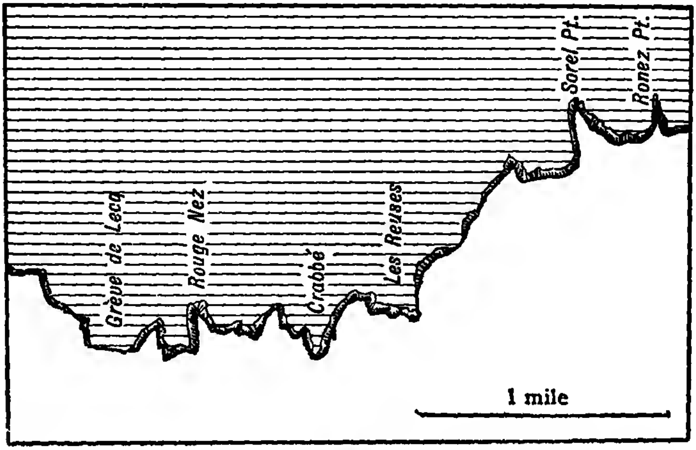
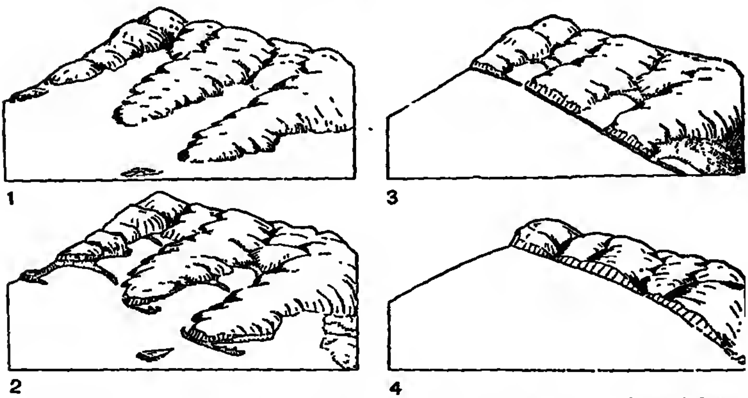


FIG. 215.—NORTH COAST OF JERSEY, SHOWING CRENULATE STAGE.



[After Johnson

FIG 216.—STAGES IN DEVELOPMENT OF SHORELINE OF SUBMERGENCE.
1, Initial stage; 2, Youth; 3, Sub-maturity; 4, Maturity.

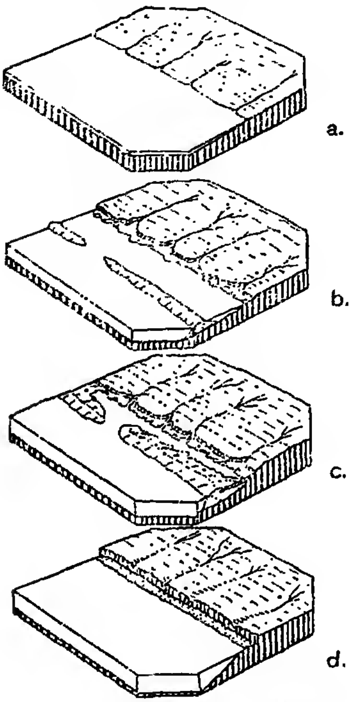
an irregular land-surface. In such a case the initial line of the shore will be exceedingly irregular. "Drowned valleys" will appear as arms of the sea, separated by headlands, and off-shore islands may also occur in large numbers. Wave-erosion will be concentrated by refraction on the

headlands and islands and, during the youth of the cycle, will cut them back rapidly. In this stage of active wave-erosion all variations in rock hardness, and divisional planes, are picked out by the waves, and the line of the exposed portions of the shore becomes complex or *crenulate.* Such a crenulate stage is well illustrated by the granite coasts of Cornwall and the Channel Islands (Fig. 215). Sea-caves are eroded along dykes, shatter-belts or major joints, and may be connected with the cliff-top area by "blow-holes." "Stacks," more or less vertical rock-masses bounded by joint-planes, stand as temporary residuals above the abrasion platform and may be seen in all stages of destruction. Thus, in the early stages the shoreline becomes more complicated, but the disposal of the debris of wave-attack soon brings about a tendency in the opposite direction. The filling of the bay-heads and the growth of spits and bay-bars simplifies the line of the shore. The complex embayed outline is replaced by smooth curves which determine the line of travel of the longshore drift. Clearly this condition is analogous to "grading" in river-action, and a shoreline so constituted may be called graded or sub-mature (Fig. 216). In this stage there will commonly be both an inner and an outer shoreline and the intervening lagoons will be in process of conversion to salt-marshes, through the accumulation of tidal or river-borne sediment. When, through further retrogradation, the shoreline has retreated behind the heads of the initial bays it may be regarded as mature (Fig. 216). Even in this stage it will not be straight, for recession will have been greatest in areas of less resistant rocks. The subsequent stages of progress towards theoretical old age will involve no striking changes in outline and need not be described in detail.

While it is possible and useful to recognize these main stages in the developing plan of the shoreline as a whole, the stages of evolution of individual constructional forms cannot be correlated in any simple fashion with the general scheme, for they depend upon highly variable factors. Before the graded stage is reached there will tend to be a great variety of constructional forms, which later tend to be merged in the simplified outline of the general outer shoreline. Local (and, in the long view, temporary) progradation may occur at any stage of the cycle, if the necessary conditions are present. The detailed vagaries of in-shore marine deposition, like those

of fluviatile deposition, march to a less orderly time than the shaping of the shoreline or landscape as a whole.

A shoreline of emergent type[1] also undergoes systematic changes in plan during development (Fig. 217). The initial line is simple, and if the off-shore slope is fairly steep, permitting the access of large destructive waves, retrogradation begins at once, with the production of a line of low receding cliffs which increase in height as they recede. Streams draining to the coast will thus be continually rejuvenated and, in general, may succeed in cutting their mouths down to sea-level, though smaller streams may be left hanging above the shore.



[After Longwell, Knopf and Flint.

FIG. 217.—STAGES IN THE DEVELOPMENT OF SHORELINES OF EMERGENCE.

(a) Initial stage. (b) Youth.
(c) Late Youth. (d) Maturity.

In the more usual case the off-shore profile is gentle, and waves rolling landward build up an off-shore submarine bank, which ultimately emerges at the surface as a typical off-shore bar. It will be breached by tidal inlets giving entrance to coastal lagoons. If these are broad enough for the generation of considerable wind-waves, the landward margin may develop low cliffs. With the progress of time the lagoons tend to become silted up with tidal and river-borne sediment, and pass to the condition of salt marsh.

The significant changes in plan in a shoreline of this type are largely concerned with the migration of the off-shore bar. Temporarily this may grow seaward by progradation but, as we have seen, it inevitably retreats landward under wave-attack and thus passes across the

[1] We shall note below (p. 357) that any shoreline of the low-lying or "flat" type imitates the "emergent" class in the manner of its evolution in plan, whatever the nature of its origin.

surface of the marshes. Marsh clays or peats are often exposed on the seaward side of such bars, giving clear proof of landward recession, but the absence of such deposits does not prove the converse, *i.e.* a stable bar, for they are removed by scour in and around tidal inlets which, over a period of time, migrate up and down the line of the bar. A well-developed off-shore bar may be regarded as the mark of youth in such shorelines. When it has retreated to the line of the mainland, full maturity may be regarded as attained. The landward retreat of the bar is, in fact, rarely uniform and some parts may reach the inner shoreline before others. In such a condition the shoreline may be termed sub-mature.

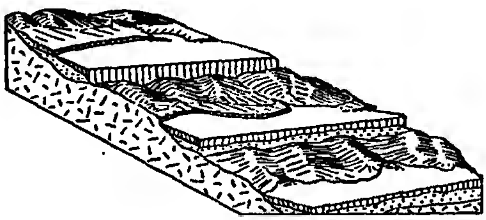
After maturity is reached, progressive retrogradation and cliffing begin, as in the case of the shores with steeper off-shore profile. Continued adjustment between process and form can be deduced theoretically, leading to the stage of old age; but owing to the general youth of the emergent shorelines available for study, actual examples of such a condition are rare or absent around the present sea margins.

Where a thin cover of younger sedimentary rocks rests on a basement of older, more resistant, rocks, and forms a narrow coastal plain, the shoreline may be cut back into the basement in the course of coastal recession. Clapp has termed such shorelines "contraposed," the term being analogous to "superimposed" in the case of rivers (Fig. 218). The sudden change in the character of the materials presented to wave-attack is an important factor in the development of the shoreline. If it had previously reached maturity it may resume the semblance of youth, and if the surface of the basement rocks is irregular, as beneath continental formations (p. 207), the irregularities may be exhumed, giving the shoreline an indented plan and a "submergent" aspect, in place of its previous emergent characters.

The classification of coastlines and shorelines.—We have distinguished between coastlines and shorelines in speaking of the terminology of the subject (p. 321), and the distinction becomes very clear when we approach the problem of classification. Coastlines studied on small scale maps, as boundaries of land or ocean regions, evidently depend for their major features on the general form and structure of the land-masses which they bound. From this standpoint we may recognize the coastlines

of much of South Africa, Western North America and many other areas as showing evident structural unity. On the other hand, the nature and stage of development of the shoreline processes and, therefore, of the shoreline details in plan and section, vary widely from point to point. Before treating of the classification of shorelines we may devote brief attention to the prior question of the classification of coastlines, since the type of coast has an evident bearing on the " initial form " presented to wave-attack.

Suess recognized a fundamental distinction between the " Pacific Type " of coastline, running parallel with the young fold-mountain ranges, and the " Atlantic Type," in which the coastline is independent of, and in general transverse to, the structure of the continental margins.

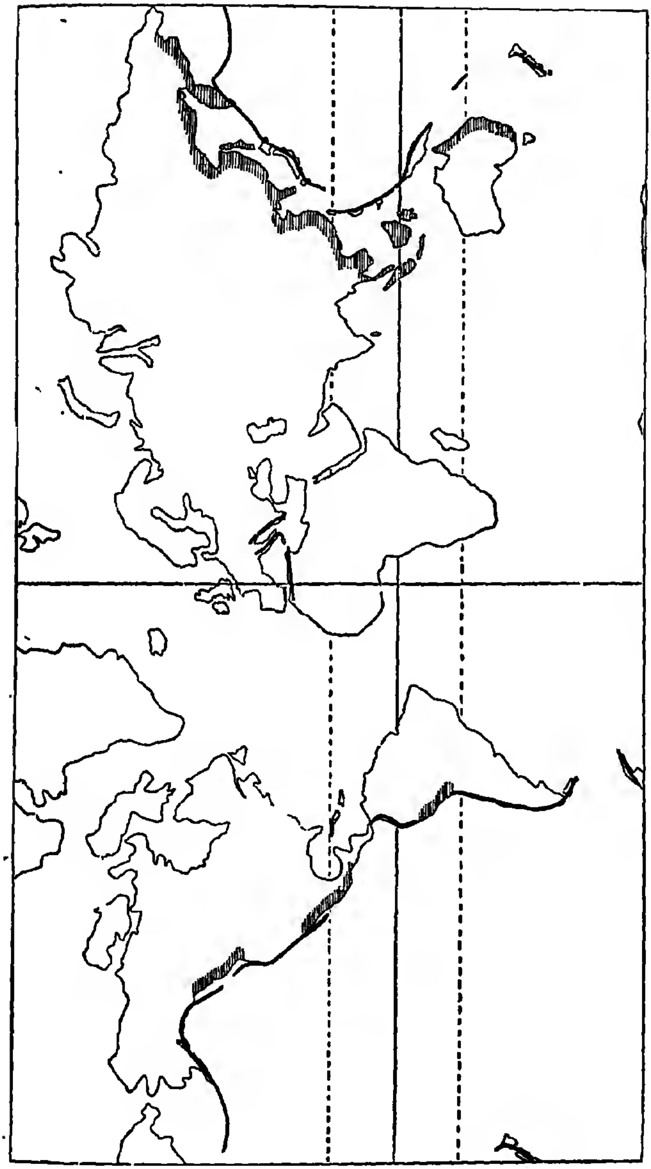


[*After Clapp and Cotton.*

FIG. 218.—DEVELOPMENT OF CONTRAPOSED SHORELINE.

First stage (back of diagram), cliffed coastal plain. Second stage, contraposition initiated. Third stage, contraposition completed, sea in contact with hard underlying rocks throughout.

Other authors have recognized this distinction and added further types to the list. Von Richthofen distinguished : (*a*) longitudinal coasts, parallel with the structural grain ; (*b*) transverse coasts, cutting across the structural grain ; (*c*) coasts forming part of the margins of foundered basins (*e.g.* around parts of the Tyrrhenian or Western Mediterranean basin) ; (*d*) block coasts, essentially the edges of plateaux (as in South and Central Africa and Eastern South America) ; (*e*) regional alluvial coasts, composed of the less resistant younger sedimentary rocks. Types (*c*) and (*d*) appear at first sight to be closely related, for whether the emphasis is on basin-edge or plateau-edge, the location of the coastline must be essentially due to fracture. In reality, however, the distinction is justified, for foundered basins are a concomitant of the younger folded mountains, while plateau-edges of the African



After Gregory.

FIG. 219.—THE DISTRIBUTION OF COASTAL TYPES.

Primary Pacific Coasts=thick line; Secondary Pacific Coasts=shaded; Atlantic Coasts=thin line.

NOTE.—This map does not mark all the coasts which might be claimed as of Pacific type, *e.g.* the west coast of Burma.

type are, if we follow modern views, symptoms of continental fission, and occur in regions unaffected by recent intense folding. Thus, types (*a*) and (*c*) are together roughly equivalent to the Pacific Type of Suess, while types (*b*) and (*d*) represent his Atlantic Type.

The conception of truly longitudinal coasts as characteristic of the Pacific Basin breaks down on the coasts of Eastern Asia. J. W. Gregory claimed that the true structural margin of the Pacific Basin, giving the Primary Pacific Type of coast, passes from Kamchatka *via* Japan, the Philippine Islands and New Guinea to New Zealand, while landward of this line is a series of collapsed basins, giving a Secondary Pacific Type of coast (Fig. 219), *i.e.* essentially type (*c*) of Von Richthofen.[1]

With these several broad structural types in mind, it will be clear that the regional " grain " of the mainland can only affect coastline or shoreline detail, where the general relation is that of submergence, bringing the water-surface against the older, more resistant rock elements in which the structures are seen. If younger sediments or recent alluvia form a coastal plain, however narrow, the general line of the coast may be transverse or longitudinal, but this fact will not affect shoreline forms unless or until the shoreline becomes contraposed (p. 351). With submergent relations, however, regional structure impresses itself clearly on coastline, shoreline, or both, through its influence on the relief of the submerged land. Thus, the drowned river valleys or *rias* of South-western Ireland (Fig. 220) and North-west Spain bring plainly to light the features of typical transverse coasts, while the similar drowned valleys (*canali* or *valloni*) of the Dalmatian coast emphasize its longitudinal structure (Fig. 221).

Fjord Coasts

The striking characteristics of fjord coasts have given rise to much controversy. In essence they resemble ria coasts, but differ in the fact that the submerged inlets have the typical form of glaciated troughs (p. 369), with

[1] The terms " concordant " and " discordant," proposed by Supan, are good alternatives for " longitudinal " and " transverse," in the general description of coastlines. The eastern coastline of the United States appears at first sight to be an exception to the " Atlantic rule " of transverse or discordant coasts, for it follows a line roughly parallel with the structural grain of the Appalachians. It should be noted, however, that the latter are not numbered among the young fold mountain ranges and hence there can be no question of a truly Pacific character. The coast really appertains to type (*e*) of Von Richthofen.

steep parallel walls, truncated spurs, hanging valleys and irregular rock-floors. The floor of a fjord is, indeed, often a true rock-basin, deeper than the sea-floor off-shore, from which it is separated by a submerged " sill." Another striking feature of many fjord coasts is the rectangular plan of the fjords and their branches (Fig. *222*). This has suggested to some observers the dominance of tectonic features, faults, shatter-belts, etc., in the formation of fjord topography. J. W. Gregory invoked special earth-movements of the nature of rifting or splitting, in the circum-polar belts where fjords largely occur. To ice-action he attributed only a subordinate role in modifying what he regarded as essentially fissure valleys. This thesis has commanded far from universal assent. There is, of course, no reason to doubt that a proportion of the fjords are structure-guided. The earlier stages of erosion were performed by water in pre-glacial times, assisted by the considerable uplift of the land then widely in progress. Ice-flow then widened and over-deepened the valleys, converting them into true glacial troughs. Since ice-erosion can proceed below sea-level till the stage of floating is reached, it is not necessary in all cases to invoke coastal depression or rise of sea-level to account for the drowning of the fjords. Submergence would have ensued naturally, following melting of the ice.

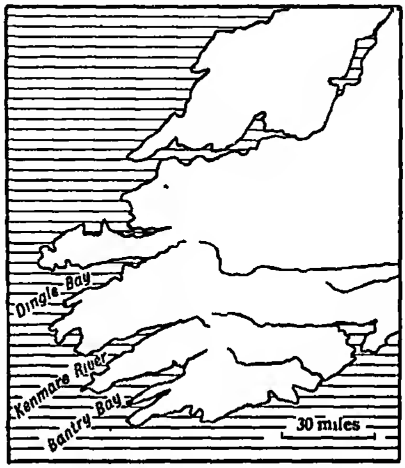


FIG. 220.—THE RIAS OF S.-W IRELAND.

195 *Shoreline Classification*

We may now turn to the problem of shoreline classification. As with all other land-forms, we are confronted with a choice between a descriptive (or morphological) and a genetic classification. Within the former category fall the various methods of expressing degree of indentation numerically, as by the ratio of actual length to the length of a simple line, tangent to the headlands or bay-heads,

or to the length of some off-shore bottom contour. Such schemes have been considerably elaborated, but of all of them the comment of D. W. Johnson is essentially true: "They tell little which a good map does not tell much better."

Turning to the genetic method, as effectively used by Johnson, we find that he announces two principles as the basis of genetic classification. In the first place, it is evident that the character of any shoreline must depend

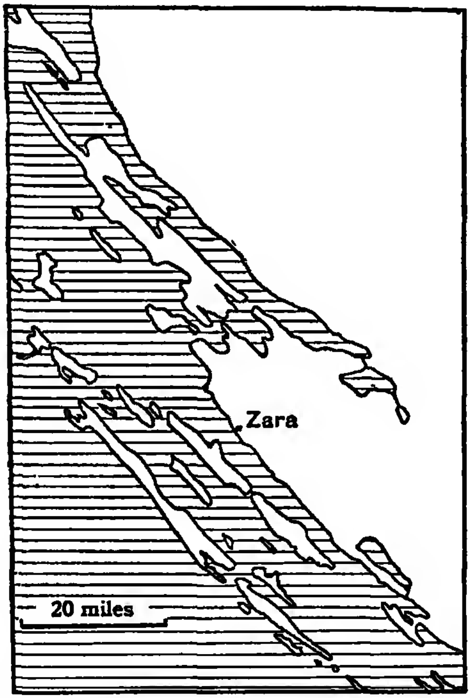


FIG. 221.—THE COAST OF DALMATIA (LONGITUDINAL TYPE).

on the character of the surface against which the sea comes to rest—*i.e.* on the *initial form*. Secondly, we must take account of the nature of the movements of land or water which brought the water-surface against the land at the present level.

Let us follow this latter principle and see where it leads us. The biggest range of contrast in initial surfaces is between irregular dissected land-surfaces on the one hand and uniform sea-floors, mantled with sediment, on the

other. If the water-line comes to rest against an initial surface of the former type, it will tend to be irregular in plan and the shore will be steep in initial profile. In the latter type the line or plan is simple and the initial profile shows a gentle and uniform slope. In this contrast lies the basis of the distinction, first emphasized by Davis and Gulliver, between shorelines of submergence and shorelines of emergence. Submergence and emergence must not be read as depression and elevation respectively. To do so would be to beg a complicated question, and it is fair to recognize that those who recommend the above terms are clearly conscious of the fact. Nevertheless, confusion is apt to result from the occurrence of shorelines of submergent aspect, in which, however, the latest act of geological evolution has been emergence, but of an amount insufficient to cancel the results of previous drowning. Probably even commoner are the cases in which an actual recent submergence has left shorelines in a dominantly "emergent" form, judged by general plan and profile. For instance, alluvial plains or land margins buried in glacial drift have in fact been submerged in post-glacial times, but from the nature of their initial form they necessarily resemble shorelines of emergence. In other words, many land-surfaces against which the waterline may come to rest resemble sea-beds in their general flatness and low slope, and if submerged by depression of the land or rise of sea-level, they may imitate the shoreline features of an emergent sea-floor. If, then, the terms "shorelines of submergence" and "shorelines of emergence" are to be used, they must be interpreted in the following carefully limited sense. "A shoreline of submergence (emergence) is one of which the dominant, not necessarily the latest,

[*After Gregory.*

FIG. 222. BUKKEN FJORD AND ITS BRANCHES.

1 inch = 15 miles (approx.).

features reflect submergence (emergence)—or one in which the features resemble those which would be produced by submergence (emergence)."

The reader will perceive without difficulty the disadvantages of this method. Nevertheless, in relation to earth history as a whole, the distinction is a fundamental one. Not once but many times, in the past, sea-floors have emerged and land-surfaces been submerged. Our practical difficulty lies in the limited time during which the actual shorelines of the world have come into being and in the all-important fact that we are living in the aftermath period of a long and complex ice-age. Recent changes of sea-level have thus been many and complex, and to interpret any section of shoreline completely we should need to reconstruct all these changes of sea-level (p. 420). In a word, we are brought back to the question of denudation chronology, which is really part of the province of the stratigraphical geologist. If we are content to leave these aspects to him, and are studying a shoreline in a context of pure geomorphology, or of geography, we can obtain useful service from the concept of shorelines of submergence and emergence. Even if we give other names to them, the two types with their contrasted morphology and development have a very real existence.

In completing a genetic classification, of which shorelines of submergence and emergence are the first two classes, D. W. Johnson adds two more, neutral shorelines and compound shorelines. Neutral shorelines are those that arise without relative change of level, by the building of the land into or against the sea. The shorelines of deltas and alluvial plains, volcanic islands and coral reefs belong to this type. The former tend to show a gentle off-shore profile, and their developmental stages tend to resemble those of the "emergent" type. The latter exhibit steeper initial profiles and more irregularity of plan, so that morphologically they have affinity with the "submergent" class.[1]

Compound shorelines combine features proper to two or more of the other classes. The preceding discussion will have indicated that in a rigid analysis many, perhaps most, shorelines are compound, but the term may be reserved for those in which no one set of class features is

[1] The fault shorelines described by Cotton from New Zealand are placed by Johnson in the neutral class, but are perhaps better grouped separately.

dominant. Johnson instances the shoreline of North Carolina, which combines submergent and emergent features in approximately equal proportions. The shoreline of West Sussex is in somewhat similar case ; the broad coastal plain signifies emergence, but the river estuaries and coastal lagoons indicate submergence.

Natural classifications grow—they are not, or should not, be made in advance. The virtue of the above simple scheme lies in its broadness and flexibility. Much more work must be done on shoreline processes and their results before a detailed scheme of classification can justly claim our attention. Meanwhile the student may perhaps feel some confusion in distinguishing coastline from shoreline classification. It would, indeed, be pedantry to push the distinction too far, and several authors have to some extent brought coastline and shoreline features into the same general scheme of classification. Thus, E. de Martonne first recognizes the fundamental distinction between flat coasts (*côtes plates*) and steep coasts (*côtes abruptes*).[1] He then distinguishes a number of subtypes, specifying type regions in some instances—viz. Lido coasts (Mexican type), estuary coasts (Maryland type), skerry coasts (Finnish type), longitudinal coasts (Dalmatian type), transverse (ria) coasts, tectonic coasts (chiefly fault coasts), epigenic (contraposed) coasts, glacially sculptured (fjord) coasts, etc.

Cotton, taking somewhat other ground, proposes, in effect, four shoreline " genera," based on the character and origin of the initial forms. The initial shoreline may be formed, by volcanic accumulation, by regional movement (either warping of land or change of sea-level), by faulting, or by glacial erosion below sea-level (fjords). Any of these may be in course of retrogradation or progradation, and in the latter case we can distinguish between progradation by alluviation and wave-action respectively. The second major group may be sub-divided into " submergent " and " emergent " classes, and the fault class can also be subdivided. This is not claimed as a complete classification, but as a working compromise bringing initial and sequential forms into relationship.

[1] These two types correspond broadly with shorelines of emergence and shorelines of submergence respectively, but it will be noted that the theoretical difficulties discussed above (p. 357) are avoided, emphasis being placed on the salient morphological characters, irrespective of origin.

In the essentially dichotomous character of these classifications the reader will perceive one aspect of the essential truth of the matter: viz. that in practical working it is inexpedient, if not impracticable, rigidly to separate coastline and shoreline features. The emphasis placed upon each must evidently depend on the scale and detail of description. Further, it will be seen that in shorelines of "submergent" type, the features of the coastline tend to dominate those of the shoreline in their effect on the general landscape, while in "emergent" shorelines, shoreline processes and the resulting forms take on the dominant role in contributing to the landscape.

CHAPTER XXII

THE INFLUENCE OF GLACIATION ON TOPOGRAPHY

Introductory.—The existing ice-masses of the world are so relatively small in extent that ice might seem at first sight to play a very minor part in the sculpture of terrestrial relief. As a fact, great importance must be assigned to glacial erosion and deposition since, as is well known, the ice-masses were much more extensive in the recent past. The present climatic phase is a mere sequel to the great Pleistocene glacial period, and few areas either in North-west Europe or Northern North America are free from the traces of the former presence of ice.[1] In many areas normal erosion has made but little progress in the work of obliterating the results of glacial sculpture and deposition. Moreover, our view of the general nature of Ice-Ages in relation to the earth's history has undergone drastic changes in the last few decades. The great masses of glacial "drift," which cumber the surface of Eastern Britain and Northern Europe, were formerly styled "diluvial" and ascribed to the Noachian deluge. Even when their glacial origin first became appreciated, the "Ice Age" was commonly regarded as the only one of its kind recorded in the rocks. It seemed natural to suppose that the sun was steadily cooling, and this view enjoyed the weighty, if somewhat dogmatic, advocacy of physical science as then understood. The "Ice Age" thus appeared as the natural culmination of this process of cooling, and the present more genial climate as merely a temporary respite from ultimate refrigeration. As early as 1859, however, true glacial deposits, resting upon ice-scratched rock pavements, were reported from much older rocks in Northern India, and though at first this discovery was treated in a rather guarded manner, as conflicting with current ideas, subsequent work has confirmed and extended it. To-day we have the clearest evidence of at least two major glacial episodes in the history of the earth, quite comparable in magnitude with the Pleistocene glaciation. The earlier episode carries us back to the time

[1] The glaciated tracts of Asia and the Southern Hemisphere, though considerable, are more limited, and less is known about them.

of the oldest known stratified rocks. In addition, half a dozen minor episodes are evidenced, and some of these may prove to be of greater importance when more is known. These facts clearly indicate that glaciation is not a rare and unique occurrence, but a systematic phenomenon, fully entitled to careful study as one of the surface processes affecting relief. It is true that only the Pleistocene glaciation has affected the present surface, but interesting clues as to the nature of ice-action and the essential unity of the process can be obtained from the older glacial rocks. Into the possible causes of the recurrent glacial climates we cannot here enter. The subject has a vast literature of a very controversial character. Broadly speaking, the numerous theories fall into two groups, the one astronomical, involving a change in the actual amount of sun heat received by the earth, the other geographical and demanding only a re-distribution of the heat as a consequence of changes in the height and area of the continents, in the plan of the general circulation of the oceans, or in the composition of the air. In the latter category we must group also the daring hypothesis of continental drift which, without radically modifying the existing zonal distribution of temperature, seeks to explain past climatic variations by a bodily movement of land-masses, their climate varying with their position.

The existing ice-masses of the world fall into two classes: (1) valley glaciers (or mountain glaciers) in mountain ranges, which discharge the accumulated snow of upland-snowfields; (2) ice sheets, like those of Greenland and Antarctica—dome-shaped masses of great thickness which almost completely cover the country on which they accumulate. It is only comparatively recently that the physics and meteorology of these larger masses have been at all adequately studied, as a result of scientific polar exploration.

Valley glaciers.—In the first place we may briefly note the features of valley glaciers. The tongue-like rivers of ice which descend from the snowfields of the European Alps and similar ranges are simple of comprehension as far as their broader features are concerned, though the details of their economy have been the subject of controversy.

The accumulation of snow above the snowline, on the flatter saddle-like tracts between the culminating peaks, is dispersed in part by melting at the lower edge, by direct

evaporation and by avalanches. Sheets of considerable thickness are, however, able to survive. At the surface these consist of powdery snow with much interstitial air. At lower levels they become compacted under their own weight into a semi-crystalline solid, interstratified with layers of true ice. Whymper gives an interesting account of an excavation made under great difficulties in a snow-field near Zermatt, and his is the first clear account of the stratified nature of the mass and its gradual passage towards true glacier ice. It is clear that this semi-crystalline mass (*névé*) is capable of flowing downhill on the steeper margins of the plateaux, and thus gives rise to glaciers at lower levels.

Though ice is said to flow, and imitates a viscous liquid in its general behaviour in large masses, it must not be forgotten that it is, in reality, a crystalline solid. Glacier ice consists of a number of irregularly-shaped ice crystals in close contact. The apparent flow arises from the fact that the ice melts at points of pressure between the grains, and the resulting water recrystallizes at points of relief of pressure. The mass thus moves on, concurrently with the change of shape and transference of material of its grains. In the upper parts of a glacier's course its constituent ice retains some of the characters of the névé of the snowfield, but in the process of movement it becomes effectively welded into a wholly crystalline mass. Its flow is affected by the form of its bed, being retarded in contact with the sides and bottom of the channel and moving fastest in midstream. The differential movement of its parts causes crevasses to open in its surface. These are particularly numerous where the floor descends steeply; in an extreme case ice-falls or "séracs" may result.

Where dominated by rocky slopes, the glacier carries debris on its surface in two or more lateral moraines, ramparts which accumulate by the falling of rock debris on to the margins of the ice. At the confluence of two glaciers, lateral moraines may merge to form a medial moraine. Material from the surface is washed down crevasses and borne forward within the ice-mass itself. Where the base of the glacier is exposed, it is seen to be full of rock-debris and mud in its lower layers. This is derived from the rocks over which it passes, and on melting forms a characteristic deposit, ground-moraine or boulder-clay. The termination of a valley glacier coincides with the point at which supply of ice from upstream equals the

amount lost by melting. If the rate of advance is sufficient, the snout of the glacier may be enclosed by a crescentic rampart comprising material disengaged from the surface of, or from within, the ice in melting. This is a terminal moraine. The melt-water from the ice escapes as a stream or a series of streams which breach the terminal moraine, and redistribute its material downward along the valley in more or less distinctly stratified deposits known as valley trains, outwash plains or frontal aprons.

The glaciers of existing mountain ranges show a wide diversity in their features of form and size. Some are now restricted to higher levels, occupying only the steep-sided valley heads, or corries, between the peaks. Others terminate many miles down the valleys. The largest of the Alpine glaciers—the Aletsch—is 10 miles long. Lengths up to 100 miles are reported from the Himalayan ranges. The Alaskan glaciers descend on to the plains and coalesce in a broad lake-like expanse, an "expanded foot," at their termination. These are called "piedmont glaciers," and although they must have been fairly generously distributed in the hey-day of the Pleistocene glaciation, Alaska alone seems to be able to furnish examples of them to-day.

A very superficial acquaintance with the glaciers of the Alps and other similar chains is sufficient to convince the observer that the recent past has witnessed a greater extension of the ice-streams. Within historic times they have shown phases both of advance and retreat in harmony with minor fluctuations or precipitation, and it requires no great effort of imagination to carry them well beyond their present limits. Where the sub-glacial rock-surface is laid bare, it is seen to be moulded into smooth, rounded shapes, while the surface is grooved and scratched. The possibility of definite glacial erosion is thereby demonstrated, though its amount is not clear.

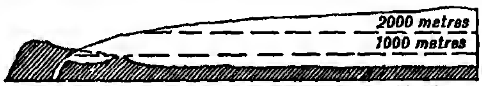
Ice-sheets.—The features of existing ice-sheets in high latitudes contrast very markedly with those of valley glaciers. Three-quarters of the surface of Greenland is covered beneath a gigantic ice-dome, which attains a height of 10,000 feet in the centre and slopes very gently towards the margins. Its thickness has been variously estimated as from 2,000 to 7,000 feet.[1] It clearly depends

[1] The latest figures for the Greenland ice-sheet are those obtained by Wegener's Expedition (1932). A seismograph was used to detect the waves set up by small dynamite explosions on the surface of the ice, some distance from the instrument. These waves passed downward through the ice and were

on the form of the buried land-mass, and the higher figure is not impossible, though the lower is perhaps more probable. Portions of the coastal regions are free from ice, and mountain summits project through its marginal portions as "nunataks" (Fig. 223). Between the latter the main ice-mass discharges to lower levels in true glaciers.

The Antarctic ice-cap is similar in its general features Recent estimates give its thickness as over 4,000 feet; considerable groups of nunataks rise above its surface. It differs from the Greenland cap in descending locally below sea-level. Thus the southern shore of the Ross Sea is formed by ice-cliffs which represent the edge of a sheet of ice projecting beyond the land and floating in the sea; the mass rises and falls with the tide.

These ice-sheets give us a much truer picture of Pleistocene conditions in Europe and North America than is



[After Daly.

FIG. 223.—THE PROFILE AND THICKNESS OF THE GREENLAND ICE-CAP.

afforded by the snowfields and glaciers of the Alps. It is to be noted that debris is generally absent from their surface except in the vicinity of nunataks, so that they do not so readily build terminal moraines. The chief accumulation for which they are responsible is true boulder clay or ground moraine. It is hardly necessary to remark that our knowledge of the conditions existing beneath them is largely inferential; it is only rarely that the base is exposed for inspection.

Glacial erosion and deposition.—The study of glacial erosion and deposition can proceed by two methods. On the one hand, attention may be paid to the physical properties and behaviour of existing ice-masses and the problems presented by the greater ice-masses of the past may thus be attacked deductively. On the other hand, we have available for study vast areas of glacially modified country. Here we can examine features formed beneath the ice, so far as they have been spared by later erosion,

reflected in part from the rock-floor. Along an east-west line, 400 km in length, extending from the west coast to near the centre of the ice-mass, the thickness was found to vary from 150 to 2,500 m., the average thickness being about 1,500 m. These results indicate considerable "basining" of the rock-floor beneath the ice-cap (Fig. 223).

and we can compare such regions with unglaciated tracts. The science of glaciology has, of course, derived its information from both sources. It may be remarked, however, that the second or inductive method has been much richer in results, for, as already pointed out, the under-surface of existing ice-masses is rarely accessible.

The study of glacial erosion was enlivened by considerable controversy during the nineteenth century. Though some measure of agreement has now been achieved, authorities are still far from unanimous. The student can obtain a good idea of the points at issue in earlier days by a perusal of Edward Whymper's description of the Aosta valley and his discussion of the views of Ramsay and Tyndall. Both the latter workers attributed great erosive power to ice. Ramsay invoked ice as the chief agent in the excavation of the numerous lake-basins of the Alpine foothills. Tyndall was disposed to deny the efficacy of ice-erosion at these low elevations, but he argued with much vigour that the Alpine valleys themselves were entirely the product of ice-erosion, a view rejected by Ramsay, who regarded them as pre-glacial valleys modified by ice. A large part of the resulting argument has lost its point in the light of later knowledge, but it retains considerable interest as a commentary on the present position. Putting the matter in its most general form, strong doubts have been expressed as to whether ice can "excavate" on an extensive scale. It is, of course, universally granted that, armed with angular rock-debris it can achieve some general smoothing, grooving and scratching of bare rock-surfaces. It is submitted, however, that this does not vouch for its power to "dig," or to remove large obstacles from its path. It is softer than many of the rocks over which it moves, and it very obviously moulds itself on to, or round, obstacles. The effectiveness of the fragments embedded in it is limited by its own softness. A lead chisel, even though armed with diamond dust, would be but an ineffective tool for cutting steel, and such is the nature of the argument presented by the opponents of extensive ice-erosion. Further, it has been cogently argued that ice and snow, as a whole, exert a protective influence on the rocks beneath, particularly when lying in thin sheets, and this proposition can hardly be gainsaid. On the other hand, it is clear that rock-masses on the floor or sides of a glacier may be frozen on to, or into, the ice and removed by "plucking" in the onward motion of the

glacier. The continuance of this process may well give rise to large effects. It is facilitated by well-developed bedding or jointing, particularly if such divisional planes are inclined at moderate angles downstream. Protuberant mounds of rock, obstructing the passage of ice, have been roughened by plucking on the downstream side, and smoothed on the upstream side, giving the "onset and lee" effect illustrated in Fig. 224.

Before we proceed to the detailed examination of glacial relief it is essential to define the main point at issue between the contending schools. Either view may be rendered ridiculous by overstatement. It being granted that ice erodes in some measure, the essence of the whole question lies in the relative rapidity and efficiency of ice-erosion on the one hand and of normal water-erosion on the other.

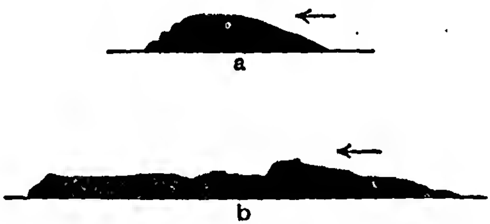
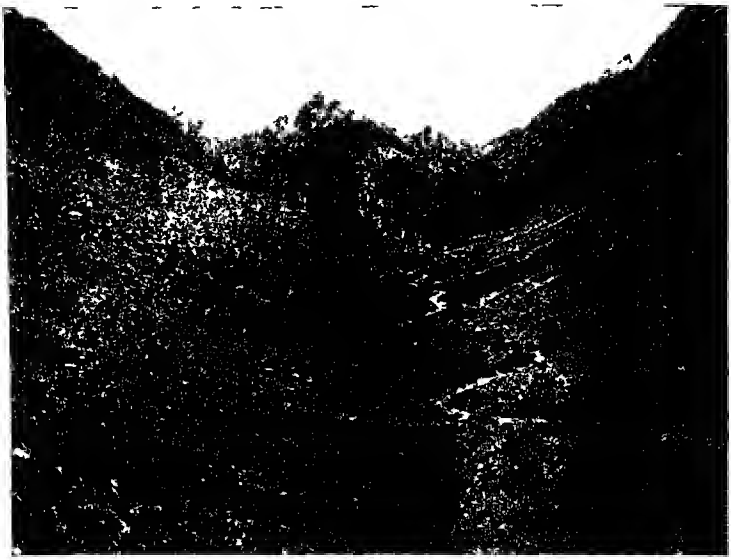


FIG. 224.—THE ONSET-AND-LEE PROFILE.
(*a*) An isolated roche montonce (10 feet high). (*b*) Holyhead Mountain (720 feet).

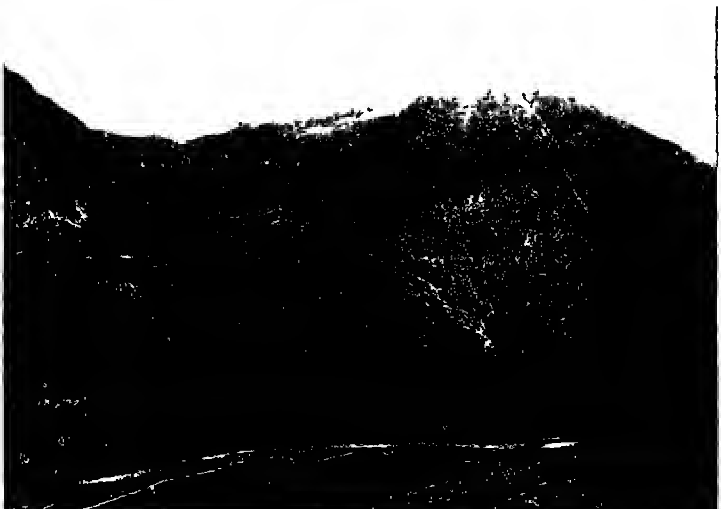
It is, of course, clear that water-erosion proceeds concurrently with ice-erosion, round the margins of the ice and beyond its limits. Of even greater importance is the fact that the Pleistocene Glacial Period embraced several distinct episodes separated by long genial intervals. One at least of these "inter-glacial periods" had a duration many times that of post-glacial time. Thus water-erosion must have alternated with ice-erosion even in the truly glaciated areas. The resulting land-forms inevitably bear the mark of both processes, and their interpretation depends on the importance assigned to each.

In the following sections we shall make a distinction between glaciated mountains and glaciated lowlands. In the former the emphasis is largely on erosion, however performed. In the latter, the most important features concern the glacial deposits or "drifts," which not only obscure the pre-existing topography, but themselves build characteristic land-forms.



[Photo by H.M. Geol Survey. Crown copyright reserved.

FIG. 225.—GLEN ROSIE, NEAR BRODICK, ARRAN, A TYPICAL U-SHAPED VALLEY EXCAVATED IN GRANITE.



[Photo by H.M. Geol. Survey. Crown copyright reserved.

FIG 226.—GLEN LYON, NEAR STRONUICH, PERTH, SHOWING HANGING TRIBUTARY VALLEY

Glaciated mountain ranges.—It has been justly remarked that the abnormal relief of glaciated mountain ranges was for long overlooked by European geographers, owing to the general rarity of true non-glaciated mountains. The ranges of Central and Southern Europe, of Scandinavia and Britain have, with few exceptions, been heavily glaciated. There was thus a tendency to regard their features as normal. Moreover, these glaciated ranges with their bolder and more varied relief are natural centres of attraction for tourists and travellers; they appear frequently in pictures and photographs, and are, in fact, the typical "mountains" of the layman. The analytical study of land-forms has now enabled us to contrast their features with those of non-glaciated mountains. The Central and Southern Appalachians provide us with an example of a maturely dissected mountain region which has been continuously under the influence of normal erosion. The Cévennes of South-east France are in a slightly more youthful stage, but, again, they are untouched by glaciation. Nearer home, the unglaciated uplands of Devon and Cornwall challenge comparison with the glaciated mountains of Wales, whose rock constitution is generally similar. In these non-glaciated areas, smooth rounded outlines are prevalent, and the general aspect of the landscape is subdued. The main streams and their tributaries are well graded, forming a many-branched system. The slopes are deeply cumbered with mantles of rock-waste. By contrast, glaciated mountains may be described as "fretted uplands." They are serrate in general form, abounding in sharp-edged features. Their drainage system is notably discordant, tributaries hanging above the main valleys. They have been scraped bare of their mantle of rock-waste, save for the scree produced by recent frost-action.

In analysing the features of the glaciated mountain landscape we shall treat of (*a*) the valleys and lower slopes, and (*b*) the peaks and upper slopes.

The valleys and lower slopes. *The Cross-profile.*—The typical cross-profile of a glaciated valley is shown in Fig. 227. Steep walls bound a flat-floored trough while, above, a pronounced bench or shoulder intervenes between the lip of the trough and the slopes leading to the higher peaks. The tributary streams descend at normal gradient across the shoulder, but plunge at its edge to the floor of the main trough. There is naturally a certain amount of variation in

detail among such glacial troughs, depending upon the character and structure of the rocks in which they are cut. The section in Fig. 227 closely follows the features of the famous Lauterbrunnen Valley, and the curiously similar Yosemite Valley in the United States. The Lauterbrunnen Valley must be regarded as a particularly fine example of its kind; the other valleys of the region are not so impressive, the trough commonly showing a more rounded or catenary form. These glacial troughs are commonly styled U-shaped, but the term is not in all respects appropriate. Comparing such valleys with normal river-valleys we may say that they combine the steep-sided nature of youth, with the breadth and flat floor of maturity. The contrast in form between a normal mature valley and a glacial trough is illustrated in Fig. 228.[1]

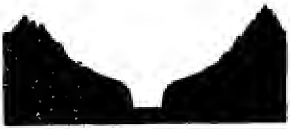


FIG. 227.—CROSS-PROFILE OF A GLACIATED VALLEY.

The distribution of smoothing and striation on rock-surfaces generally shows that the ice extended on to the shoulder, or even above it, in its passage down the valley, so that only its lower parts occupied the trough. The bevelling of the shoulder edges and the filling of the basal angles with alluvial fans and scree give the measure of the normal frost, gravity and water-erosion of post-glacial times.

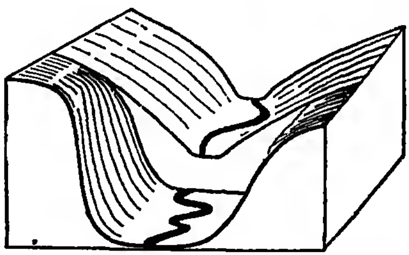


FIG. 228.—CONTRAST BETWEEN WATER- AND ICE-ERODED VALLEYS.

In such valleys as these the advocates of extreme glacial erosion, as favoured by Tyndall, would regard the trough as literally dug out by the passage of the ice. Other workers would refer the excavation of the trough to normal river-action in pre- or inter-glacial times, and its final shaping, involving considerable widening and some deepening, to the subsequent work of ice. The shoulder, though glacially

[1] It should be noted that since ice occupies the whole of a glaciated trough, the latter is comparable with the *channel* rather than the *valley* of a river. Viewed from this standpoint the channels cut by ice and water respectively are not markedly dissimilar in form, but only in size.

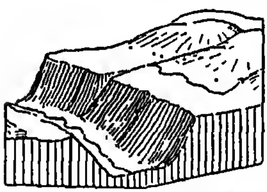
modified, thus falls into place as the floor of an older and wider valley in whose floor a water-cut gorge was incised. In Fig. 227 only one shoulder is shown, but many Alpine valleys show several, extending up to great heights above the present valley-floor (Fig. 229). The valley slopes in such a case convey a strong suggestion that they are normal composite slopes, developed during successive phases of normal down-cutting alternating with glacial interludes.

[After de Martonne.

FIG. 229.—MULTIPLE SHOULDERS OF THE AAR VALLEY NEAR MEIRINGEN.

Hanging Valleys

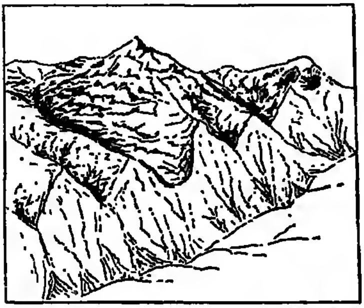
The hanging tributary valleys (Figs. 230, 231) are explained by the ice-erosion school as the consequence of differential over-deepening as between the main glacier and its less voluminous and active affluents. On the ice-surface the streams would necessarily be concordant, but the floor of the main glacier is regarded as having been excavated far below those of the tributaries, so that marked discordance has inevitably arisen on the disappearance of the ice. The supporters of glacial protection take very different ground. Regarding the over-deepening of the main trough as due to river-action in an inter-glacial period, they urge that the tributary valleys at a higher level would retain in some cases a small glacier, whose presence would inhibit normal water-action and thus retard the grading of the tributaries. They find strong support for this view in the fact that not all the tributaries of a glacial trough hang to the same extent. Within short distances one may find instances both of precipitous "hang," and of roughly accordant tributaries whose valleys, it is supposed, retained no protecting glacier, and in which, therefore, the work of grading made headway. Particularly significant is the fact that tributary valleys facing north and east, *i.e.* on the slope turned away from the sun, frequently hang, while those of the opposite slope are accordant. The tributaries of the Reuss near



[After Cotton.

FIG. 230.—A HANGING VALLEY.

St. Gothard have been cited as an illustration of this relation. The evidence presented on this score seems highly convincing, and though there is no reason to doubt that a large glacier erodes faster than a small one, and that discordance may at least be initiated in that way, differential corrasion as between large rivers and small glaciers seems certainly to have played a large part in the causation of hanging valleys.



[*After Davis.*

FIG. 231.—HANGING VALLEYS.

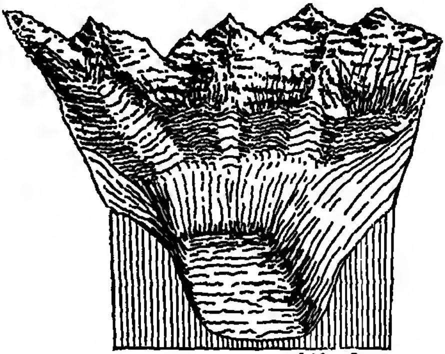
The Glaciated Valley in Plan

The features presented by a glacial valley in plan also bear upon its origin. Its course is characteristically straight, and it commonly retains traces of the " roots " of valley-side spurs, whose blunting or truncation must have been the work of ice. It is particularly to be noted, however, that the existence of the spurs, even as vestiges, within the trough clearly implies the former operation of water-action, and thus lends strong support to the views of the " protection school." Truncation of spurs is a phase of valley widening, and, as such, falls within the power of ice-erosion, as admitted by all. The act of valley deepening would seem to be largely referable to water-action.

The Long-profile

The longitudinal profile of a glaciated valley reveals further abnormal and significant features which challenge explanation by exponents of the two views of glacial action. The profile is typically irregular, descending in a series of steps. The most considerable of these often occurs at the head of the true trough where the convergent headwaters of the stream now occupying the valley descend in gorges to the floor. This highly characteristic " trough's end " is well illustrated in the Lauterbrunnen and Zermatt Valleys in the Swiss Alps (Fig. 232). Steps of smaller magnitude, lower down the valley, are so common as to be regarded as normal concomitants of glacial erosion. Good and readily accessible examples occur near Burglauenen in the Grindelwald Valley and above Täsch in

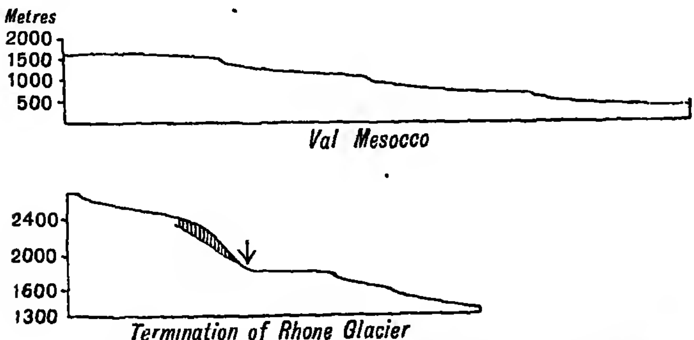
the Zermatt Valley. Garwood instances in some detail the Val Mesocco, tributary to the Ticino above Bellinzona (Fig. 233). Here there are three steps, respectively 300, 500, and 800 ft. in height, the height increasing with ascent of the valley. Such steps may be actual cliffs or merely steep slopes; the present stream has generally cut a gorge in descending the step and recession may have carried its head some distance above the step itself.



[After Cotton.

FIG. 232.—THE MAJOR ROCK-STEP OR "TROUGH'S END."

The supporters of active glacial erosion explain these steps by inequality of downward corrasion. A few mark obvious differences in rock hardness, and it has been plausibly urged that glacial erosion may pick out differences of hardness which escape detection on ordinary examination. Again, it has been widely accepted as axiomatic that



[After Garwood.

FIG. 233.—ROCK-STEPS OF THE VAL MESOCCO; AND NEAR TO, AND BENEATH, THE TERMINATION OF THE RHONE GLACIER.

the erosion effected by an ice-stream varies as its volume, or thickness. Hence, we might expect an increase in down-cutting power below the confluence of two glaciers, particularly if the cross-section of the

combined ice-stream is much greater than those of its contributing parts. This relation is sometimes observed, and no doubt the sudden deepening at the "trough's end" reflects in part the convergence of ice-streams from higher levels at this point. The position of the "erosion school" is perhaps not unfairly summed up in the statement of one eminent exponent that "if it were once proved that glaciers erode their troughs . . . some inequality of erosion was as likely as in the erosion of a channel by a river." On the other hand, the protection theory has a salient contribution to make to the problem of the steps. Since it is known that the glacial period witnessed several marked advances and retreats of the ice, a step is regarded as marking the limit of retreat of the ice in the valley during some inter-glacial phase. Below this point water corrasion would be resumed and the valley would be deepened up to the ice limit. During a re-advance of the ice the step thus formed would survive the widening by glacial erosion, always providing the ice exerted no pronounced deepening effect. Where several steps occur in the same valley, this theory demands a succession of glacial advance and retreats. The relative magnitude and spacing of the steps of the Mesocco valley are shown by Garwood to accord well with the accepted sequence of glacial episodes in the Alps. Furthermore, there is in this region a general agreement between the several valleys in respect of the height above sea-level at which the steps occur. Such is clearly a necessary condition, if the theory is to fit the facts.

Rock-basins

A further aspect of the problem of glacial erosion is involved in the origin of "rock basins." Not only is the longitudinal profile of a glaciated valley broken by steps, but the downstream gradient of the floor may locally be reversed, giving a rock-bounded hollow occupied either now, or in the past, by a lake. Similar depressions at higher levels, on the shoulders of the valley, are often occupied by "tarns," while in the outer valleys and piedmont margins of the Alps are the larger lakes, also claimed by some as rock basins. The existence of such hollows has been regarded as a clear proof of the reality of localized ice-erosion, but, on the other hand, it has been strenuously contended that erosion during "uphill movement" is impossible. The bottom ice, lodged in some pre-existing

hollow, would be expected to remain stagnant while the upper layers passed over it. In the case of the smaller valley lakes and upland tarns of the Alps it has been successfully demonstrated that some are held up by barriers of loose rock material, moraine, or scree. Others are undoubted rock basins, but they are located on the boundary between soluble calcareous strata and insoluble rocks. These form a distinct class of "solution lakes" which have no necessary connexion with glaciation, and are, in fact, well-known in the karst lands of many areas. Other rock basins are not so situated, and here it may fairly be supposed that glacial "plucking" by the bodily removal of fissured or jointed rock has produced a cavity. The reality of this plucking action is sufficiently evidenced by the numerous lakes, many of small size and irregular shape, which are scattered over the surface of glaciated lowland areas formed of hard crystalline rocks, such as the Canadian Shield and Finland.

The larger lakes present difficult problems. Many, following Ramsay, have preferred to regard these as the product of over-deepening performed by ice in large valleys, or by the vast piedmont accumulations of ice at and beyond the mountain foot. By others the influence of tectonic warping has been invoked.

The peaks and upper slopes.—The land-forms of the higher parts of glaciated mountain ranges are quite as characteristic as those of the valleys, and these, too, have been the subject of considerable debate. It is these features that control the general panoramic character of a range as viewed from one of its own higher summits or from a distance. We may select three features: the *arète*, the *pyramidal peak*, and the *corrie*, as recurrent elements in the pattern and profile of glaciated heights. The arête is a sharp-edged ridge made of bare rock, with its summit either roughly horizontal or inclined. Inclined arêtes generally converge on one another, and at their point of meeting are situated the culminating peaks. These are generally sharply pointed and have a rough pyramidal form (Fig. 236). The familiar Matterhorn is a magnificent example of this form, somewhat unusual in the fact that it is isolated and rises above a generally flat plateau-like surface. Between the convergent arêtes are remarkable hollows, open on one side, but bounded elsewhere by an almost semicircular or sub-rectangular line of cliffs. These have been given a distinctive name

in most European languages (corrie, in Scotland; cwm, in Wales; cirque, in France); and they are, perhaps, the most significant feature of glacial sculpture in the higher slopes. Their floor is commonly occupied by a lake, of which the outlet is dammed either by moraine or by a definite rock-bar. Their form has been compared with that of a gigantic armchair, with the seat slightly hollowed (Figs. 234, 236).

[After Wright.

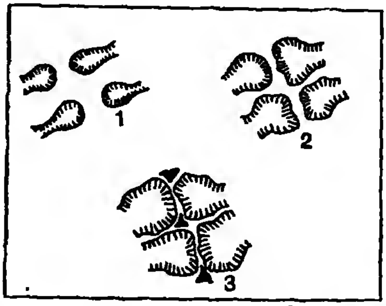
FIG. 234.—A CORRIE GLACIER, WITH BERGSCHRUND AND MORAINE.

The Corries

At first sight a typical corrie bears some resemblance to the valley-head amphitheatre produced by normal erosion. The latter, however, is as a rule " half-funnel shaped " with comparatively gentle slopes. The slopes of a corrie are much steeper, and the rock basin in the floor constitutes another departure from the form of a normal valley-head, though admittedly it is not always present. Like the features of the lower valleys, corries have been the subject of opposed arguments by writers on glacial morphology. It is, of course, clear that many corries are nothing more than modified valley heads; but others abruptly break the continuity of smooth hill-slopes, and for these, at least, some definite theory of origin is required. Garwood contends that some element of glacial protection is necessary to explain the distinctive form. The preservation of many corries is to be directly attributed to their having harboured snow or ice during inter-glacial and post-glacial times, during which the surrounding slopes, both above and below, were the subject of steady demolition under the influence of frost, water-erosion, and soil-creep. It is not to be forgotten that such a process is visibly in operation to-day in many cases where corries retain, during the whole or part of the year, a mass of névé in their hollows.

On the other hand W. D. Johnson has described a process of " basal sapping " which has been regarded by many as the active process of corrie excavation, and especially of the steepening of the walls. He points out that in an ice-filled corrie, as in most steep snow- and ice-slopes, there is a marked crevasse or " bergschrund,"

which follows the margin a few feet away from the rock-wall. This is due to the general " pull-away " of the ice from the wall, incidental to its movement. It converges on the rock-wall downwards, and finally meets it some distance below the surface of the ice. Here a large area of rock-wall is subject to frost-shattering, being soaked during the day by melt-waters from above, which freeze during the night. In this way large blocks are displaced from the face, and frozen into the ice on the other side of the crevasse, subsequently to be carried away in the onward motion of the ice. It is certainly not safe to assume that this " bergschrund hypothesis " covers all cases, but in so far as the idea is valid it provides conditions for " plucking," and offers a mechanism for the " arming " of the corrie glacier with angular rock debris in its lower layers, and thus helps to explain the excavation of a shallow rock basin on the floor.



[After Hobbs.

FIG. 235.—DISSECTION OF UPLAND BY CORRIE-GROWTH.

1, Stage of Youth—a " grooved upland." 2, Intermediate stage. 3, Stage of maturity—a " fretted upland."

The precise view taken of the origin of the arêtes and pyramidal peaks or tarns depends very largely upon the extent to which it is admitted that corries actively " grow " by ice-erosion. W. H. Hobbs has treated the development of corries in terms of a cycle. He supposes that the initial hollow is in many cases a " nivation hollow " (p. 402). Then, adopting the bergschrund theory of excavation, he deduces a systematic and long-continued recession of the walls, leading first to a semicircular and, later, to a more rectangular plan, while, concurrently, a scalloped edge develops as a result of the formation of minor corries. In this view a mountain-mass is dissected in stages by corrie growth, in a manner analogous to dissection by water (Figs. 235, 236). Marked cols arise by the intersection, back to back, of actively growing corries, and, in general, the peaks and ridges are simply residual features of such a process of dissection. Hobbs distinguished the " grooved upland," marking an early stage

of corrie dissection, from the later "Sc" fretted upland," in which the residual features are more scattered and less extensive. In the limit, such a process would result in the complete destruction of the original surface—a state analogous to maturity in the normal cycle of erosion. This attempt to establish a glacial cycle is attractive and useful, but as yet it is not based upon a sufficiently numerous set of carefully studied examples, and it would be premature to accept the theory in its entirety. The more orthodox view would refer the "sharpening" and demolition of peaks and ridges to the active agency of frost, aided by gravity, and in such a view the corries are relatively static elements not susceptible of considerable enlargement, but owing their clean-cut form to the protective influence of ice during phases of normal weathering and water-erosion.

[*After Davis.*

FIG. 236—GROWTH OF CORRIES, LEADING TO ISOLATION AND ULTIMATE DESTRUCTION OF PYRAMIDAL PEAKS

Deposition contributes a small element only to the morphology of glaciated mountain ranges. The floors of the valleys are generally covered with ground moraine, though often to no great depth. Retreatal stages of the ice in the valleys are marked by "stadial moraines,"[1] but the earlier moraines of such a series have lost their freshness of form in the course of later weathering. At their maximum extension many of the Alpine glaciers were of piedmont type, and their expanded termination on the low ground is marked by a set of features which recur in close association many times. A more or less semicircular end-moraine, consisting of one or more distinct ramparts, encloses a slight depression in the ground-moraine in which a lake commonly occurs. Between the end-moraine and the lake-depression is a zone in which the boulder-clay is disposed in elongated mounds ("drumlins") with their longer axes radiating so as to be roughly normal to the moraine front. Beyond the moraine stretches a flat plain or apron of outwash gravels (Fig. 237),

[1] In strict usage "terminal moraines" are those marking maximum extension of the ice, while "stadial moraines" mark stages of retreat, though the former term is often used in a general sense covering both cases

the so-called "deckenschotter." Outwash gravels extend down the Alpine valleys far beyond the limits reached by the ice. They are disposed in terrace-like spreads above the present valley-bottoms, and they represent a series of definite stages which may be correlated with waxing and waning of the ice-masses (p. 406 and Fig. 260).

Glaciated lowlands.—Glacial drifts play a much larger part in determining the topography and surface conditions of glaciated lowlands. The uplands have retained for the most part the major features of their pre-glacial form, subject to some emphasis of their relief, but the lowlands have been completely reconstituted by glacial action, so that their pre-glacial features have entirely disappeared. If the drifts were removed from England large areas on both the east and west coast would be covered by the sea, *i.e.* the base of the drift is below sea-level. In addition there are extensive tracts, where, though the base of the

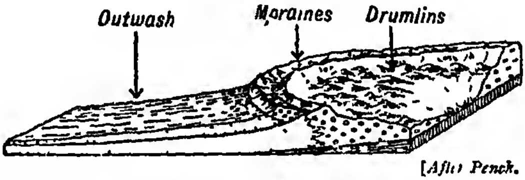
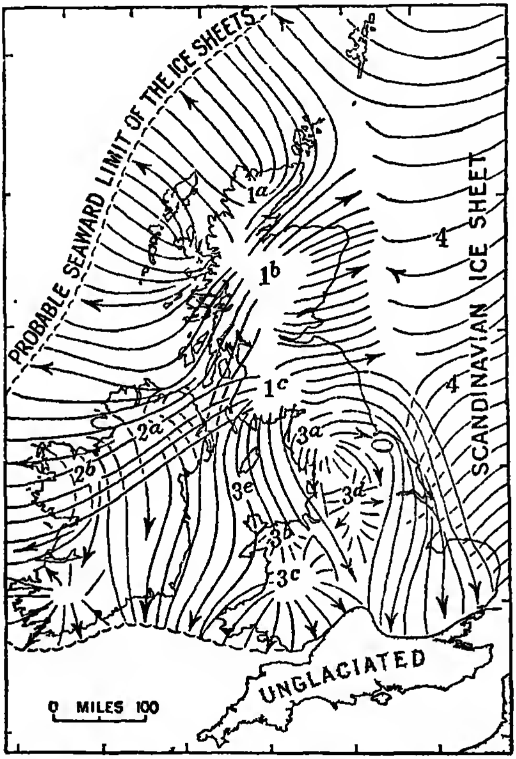


FIG. 237.—FEATURES MARKING FORMER TERMINATION OF A VALLEY- OR PIEDMONT-GLACIER.

drifts is above sea-level, they are the dominant elements in the country, older rocks being exposed, if at all, in the valley-bottoms only (Figs. 238, 239).

Boulder Clay.—These vast sheets of lowland drift are clearly the product of the Pleistocene ice-sheets, whose nature differed widely from that of valley glaciers. In particular, as we have noted, debris must have been largely absent from their surface, and well marked terminal moraines are relatively infrequent in the region of maximum extension of the ice. The drifts include two main types of deposit: (*a*) boulder-clay, which is interpreted as ground-moraine, or "englacial" material left by slow-melting, and (*b*) bedded sands and gravels, deposited by water at the margin of the ice, beneath it, or beyond its limits. In the case of an actively advancing ice-sheet we should expect it to push forward over its own outwash gravels, forming a sheet of ground-moraine above them, while during active retreat more water-deposited

gravels would tend to accumulate on the surface of the boulder-clay. This threefold arrangement of: (1) Gravel; (2) Boulder clay; (3) Gravel, is indeed not infrequently found. On the other hand, two boulder-clays separated by a sheet of sands and gravels occur in so many regions



[*From Stamp and Beaver, "British Isles," Longmans, Green and Co.*

FIG. 238.—THE GLACIATION OF BRITAIN.

The map shows approximate conditions at the stage of maximum glaciation. Directions of ice-movement shown by arrows. Centres of ice-dispersal: 1*a*, N.W. Highlands; 1*b*, Grampians; 1*c*, Southern Uplands. 2*a* and *b*, N. Ireland. 3*a*, Lake District; 3*b*, North Wales; 3*c*, Central Wales; 3*d*, S. Pennines; 3*e*, Irish Sea.

that this arrangement has sometimes been regarded as normal or typical. It may be interpreted as marking a temporary local retreat of the ice-margin followed by a re-advance; or if the intervening mass of water-laid deposits is thick and extensive, a definite interglacial phase may be indicated. The distinction is really one of degree only,

and high authorities can be found to support both views in such a region as East Anglia, for instance, where this second type of tripartite arrangement is well illustrated.[1]

Though local successions in the glacial drifts can often be plausibly ascribed to oscillations, large or small, in the ice-margins, we have to recognize the fact that there are large areas in Western Europe and America in which the boulder-clays are not associated with gravels, either above or below. The absence of gravels above the boulder-clay seems at first sight particularly anomalous, for it is difficult to see how a large mass of ice could melt without providing floods of water which would wash out the debris from the ice, or from the boulder-clay itself. The progress of observation in the ice-bound regions of high latitudes has gone far to afford a clue to this feature. In Spitzbergen and elsewhere the ice has sometimes advanced over the low ground, but there has been no correspondingly rapid retreat. It has simply been left as "dead ice," decaying by melting very slowly and without the production of large quantities of water. In this way the englacial debris is slowly disengaged and settles down as a sheet of material which in many cases resembles the boulder-clay of the North European plains. In such a case, needless to say, no terminal moraine is formed. There are many accordant observations upon valley-glaciers and existing ice-sheets, which point to a spasmodic or pulsatory advance followed by long inert periods of

[*After Lamplugh and Wills.*

FIG. 239.—THE DRIFT LANDS OF ENGLAND AND WALES.

The stippled areas are almost wholly drift-covered; while the areas in black would be submerged if the drifts were removed. Certain areas of post-glacial alluvium are included with the glacial drifts.

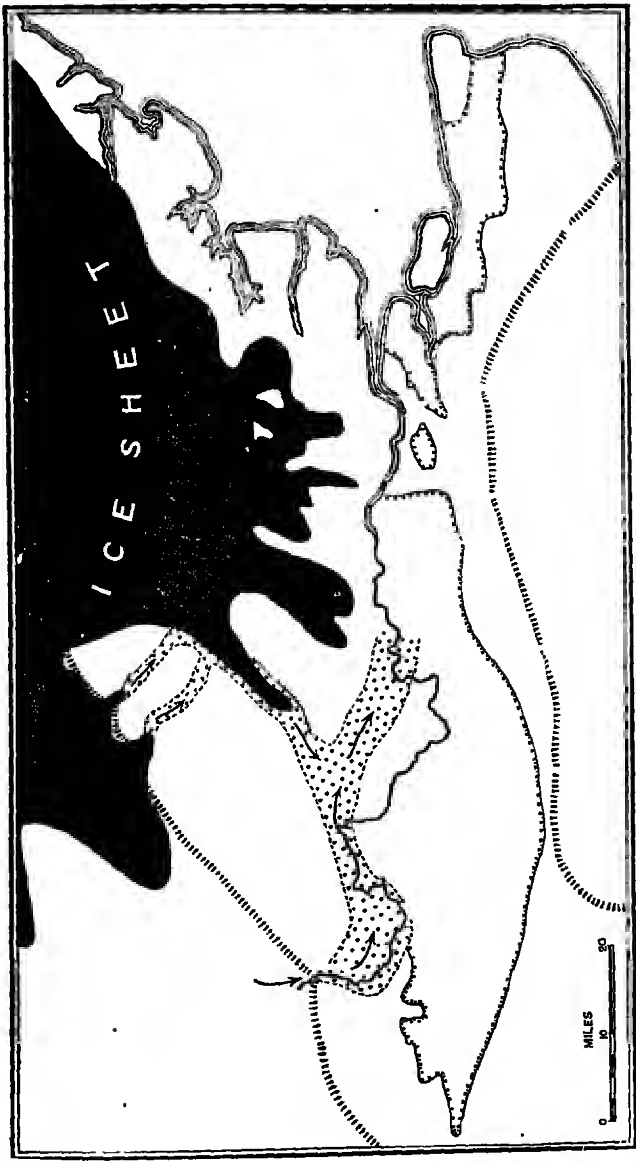
[1] Recent work by Boswell and Solomon leaves little doubt that several distinct glacial episodes, separated by inter-glacial periods, are represented in the East Anglian drifts.

exhausted energy. The cause of this phenomenon is not entirely clear; the rapid advances may possibly mark the attainment of a certain necessary or critical "head" of snowfall, while the pauses may mark the periods of accumulation. However this may be, the effect seems to be general, and it is entirely reasonable to suppose that the Pleistocene ice-sheets behaved in a similar way. Following this idea Lamplugh has suggested that "the maximum extension was reached by a final forward spurt," after which "the ice sank into a dead condition and never again revived." In this fashion the existence of extensive gravel-free boulder-clay plains may be plausibly explained.

Boulder-clay Country

Quite apart from the presence or absence of gravels, "boulder-clay country" is of several distinct types. The consistency and contents of the deposit are, of course, infinitely variable. It has often received a large contribution from the rocks on which it rests, and for this reason alone shows local variations. It contains, in addition, much far-travelled debris, which gives it a mixed constitution. In Southern England, where the boulder-clay abuts upon other clay tracts (London Clay, Oxford Clay, etc.), it affords soils at once richer and lighter than those of the stiff clays, and makes better agricultural land. Its woodland was lighter and more easily cleared, so that its outcrop was settled at an early date and shows a marked unity in respect of human geography.

Further, from the standpoint of morphology the British boulder-clay areas fall into two types, and analogues of both can be found both in Northern Europe and America. In East Anglia, Essex and Hertfordshire, the boulder-clay forms a vast level-topped sheet, diversified only by rather widely spaced valleys in which post-glacial erosion has cut down into underlying rocks. It thus forms a low plateau, not yet maturely dissected. The only irregularities in its surface are small hollows, generally holding water, but many of these have been filled by rainwash. The margin of the boulder-clay sheet is irregular, and it is evident that the ice, here of no great thickness, forced its way in lobes or tongues between the masses of high ground. Beyond the extremities of such lobes a dissected sheet of outwash gravels is generally found, but no end-moraines mark the limit of the boulder-clay (Fig. 240).



[S. W. W.

Fig. 240.—The Glaciation of the Area North of London.
Note the lobes of the ice-sheet, projecting between masses of higher ground, and also the valley-trains of fluvo-glacial gravels.

Drumlins.—On the other hand, the boulder-clay tracts of the Midland Valley of Scotland and South-west Ireland are characteristically hummocky, consisting of a complex series of drumlins. We have noted that similar features were produced beneath the valley glaciers of the Alps. The origin of the drumlins is somewhat obscure.

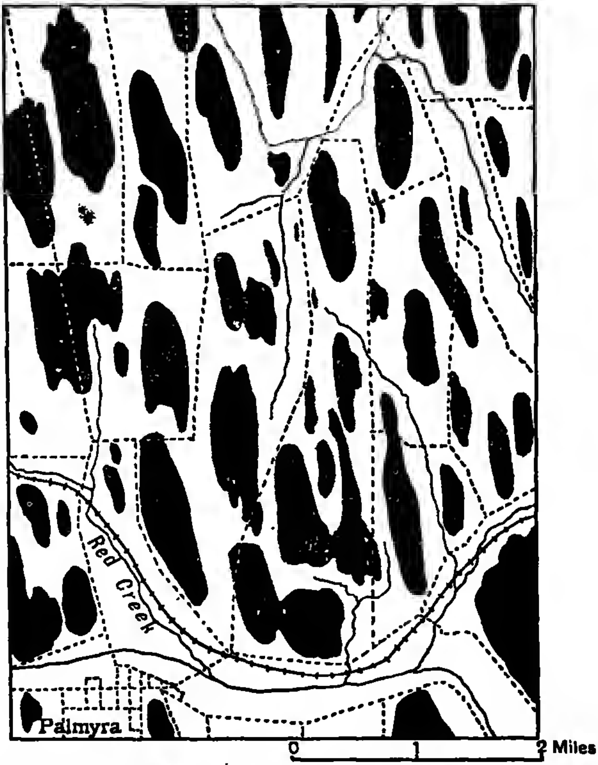


FIG. 241.—DRUMLINS, NEAR PALMYRA, NEW YORK STATE.
The larger drumlins rise about 100 feet above the flat intervening ground.

In form they resemble an inverted boat, tapering towards their ends. They range in size from mere flat swellings of the ground, disposed confusedly *en échelon*, up to considerable hills, 200 or 300 feet in height (Fig. 241). Their longer axis generally follows the direction of ice-movement, although there are exceptions to this rule. They are composed entirely[1] of boulder-clay. It is

[1] The term has been extended by some authors to cover the case of "rock-drumlins," smoothed mounds of rock with or without a thin veneer of boulder-clay.

generally considered that they correspond to patches in the sole of the moving sheet which were exceptionally heavily charged with debris. Ice so charged has its effective powers of flow considerably reduced, and in such circumstances the clearer ice, around and above the concentrated " knot " of debris, would move on more rapidly. On the melting of the ice-sheet, the hummock of " dirt " would settle down as a drumlin, through the slow melting of its interstitial ice. The streamlined form of the hillocks is regarded as due, in part, to the differential movement of the clear and the rock-charged ice during the earlier phases of growth. This theory is perhaps not entirely clear and satisfactory, and it illustrates our inevitable ignorance of sub-glacial processes which are beyond the range of direct observation. An attempt has been made to argue that drumlins are not sub-glacial features but result simply from the post-glacial etching of boulder-clay sheets by normal erosion. It is significant, however, that similar features are rarely found in other claylands exposed to normal erosion, and in the opinion of most students of glaciology the theory fails to meet the facts.

The geographical effects of drumlin topography—sometimes called " basket-of-eggs topography "—are sufficiently evident in many areas. The drainage tends to be irregular and indecisive, and many small tracts of marsh or water-logged pasture occur between the drumlin hills. Settlements and routeways thus favour the drumlin crests or slopes.

We may have recourse to two explanations of the difference between featureless boulder-clay plains and those diversified by drumlins. It may be urged that drumlins only arise when the sub-glacial load is unevenly distributed, a uniform distribution giving rise to a uniform sheet of ground-moraine. More probably, however, we are witnessing the difference between a sheet of true ground-moraine, moulded by moving ice (drumlin-topography), and a sheet of englacial material abandoned by the slow decay of " dead ice " (East Anglian type). In support of this we may note it is particularly in boulder-clay flats of the East Anglian type that superficial gravels are absent, and we have already invoked the process of slow decay *in situ* as a plausible explanation of the absence of such gravels.

Eskers and Kames.—Areas of hummocky drift generally display not only drumlins but ridges of sand and gravel,

[Photo by H M Geol Survey Crown copyright reserved

FIG 242 —ESKER AND ESKER DELTA MOCKERKIN TARN NEAR ULLOCK, CUMBERLAND

The steep bank beyond the tarn is the side of the esker, which expands to form an esker delta near the road on the right (p 387)

[Photo by H M Geol Survey Crown copyright reserved

FIG 243 —TERMINAL MORAINE IN GLEN ETIVE, NEAR DALNESS, ARGYLE.

equally distinctive in form and disposition. We may pass to the consideration of these. Mounds and ridges of gravelly drift are referred to in British glacial literature as eskers and kames, or, generally, as kettle-drift or kettle-moraine. They are regarded as formed by water or at beyond the margins of the ice.

Eskers (comparable if not identical with the Swedish "ösar") are long sinuous ridges with steep sides, composed of gravel and sand (Fig. 242). They may be followed across country for considerable distances, though sometimes discontinuous. Among their notable features is the fact that they sometimes ignore the ordinary topography, descending one valley-slope and ascending the other. In order to explain them we have to take note of the fact that existing ice-masses are riddled by tunnels, which carry the melt-waters from higher levels. For instance, the expanded "piedmont" foot of the Malaspina Glacier (Alaska) presents a high terminal ice wall, and vast quantities of water emerge from tunnels at the foot of the wall, or cascade from openings high in the face. Water travelling in such tunnels attains high velocities, owing to the constricted space and the ample head provided by downstream slope. It is certain that eskers are closely bound up with such channels. One ingenious theory represents these ridges as the "casts" of sub-glacial channels entirely filled with sand and gravel, while the ice-cover persisted, and preserved in slightly modified form after melting. This would account for their curiously discordant relations to surface topography, since, formed under the ice, they would be independent of uphill or downhill slopes. It is not unlikely that some eskers formed in this way; but, for many, another suggested origin better fits the facts. At the present time deposits are being built at the points of emergence of sub-glacial streams on the stationary ice-fronts of the Alaskan piedmont glaciers. They are banked against the ice-wall behind, and where formed on land, slope forward fanwise to a more or less irregular or lobate front, thus imitating normal alluvial cones (Fig. 244). In other cases the deposit has been built beneath standing water, and takes on the characteristic delta form with a flat top and a steeply sloping front (Fig. 244). Where the ice has withdrawn locally, the back face, formerly in contact with the ice, may retain a characteristic steepness and may be recognized at once as an "ice-contact slope." Many

eskers associated with the American and Scandinavian drifts have been claimed as originating in this way, and good examples have recently been studied in Cumberland and in Shropshire. It is evident that if the ice were retreating rapidly the products of a single sub-glacial stream would be distributed over the country as a ridge or trail, instead of being concentrated in a fan or a delta.

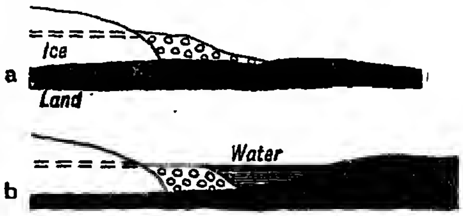


FIG. 244.—WATER-BORNE DEPOSITS ACCUMULATED AT ICE-FRONT. (*a*) Esker-fan. (*b*) Esker-delta.

Such is clearly the nature of many eskers. Each pause, or ice-stand, will be marked by a swelling of the ridge, and thus a series of fans or deltas may be strung along the "feeding esker," like beads on a string (Fig. 245). To such a form the term "beaded esker" is applied. Alternatively, there may be a series of discontinuous mounds aligned in

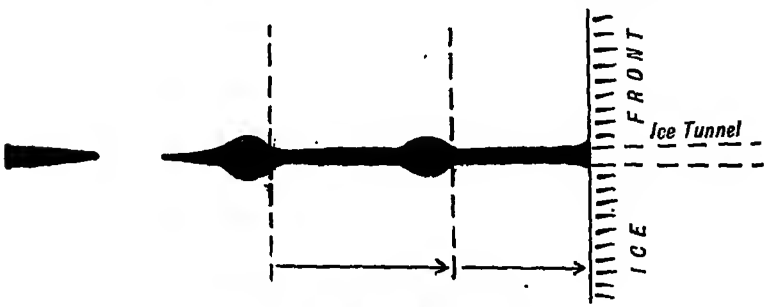


FIG. 245.—A BEADED ESKER.

the direction of glacial retreat, with or without feeding esker ridges. Fig. 258 shows an example of such an esker-chain, which extends for a distance of nearly twenty miles between Wolverhampton and Newport, Salop. A short distance to the north-east is the Penkridge esker, which is in alignment with a curious channel unrelated to the present drainage plan, interpreted as having been excavated by the esker-building stream.

The term "kame" has been applied to a variety of features, but in many cases the mounds or ridges so named appear to lie along the line of a former ice-front and to represent the confluent fans or deltas of a series of closely spaced sub-glacial streams. We may instance the great drift-ridge at Carstairs in Southern Scotland as an example of a kame. It separates a low-lying area of alluvium to the north-west from a plain of outwash gravels to the south-east (Fig. 246). It rises to a maximum height of about eighty feet above the low ground at its north-western foot, and its steep north-western slope appears to be an ice-contact slope. On the other hand, this feature has been claimed as a terminal moraine or as the infilling of a channel between ice-walls during a phase of glacial melting. The latter theory affords no explanation of the pronounced asymmetry of the ridge.

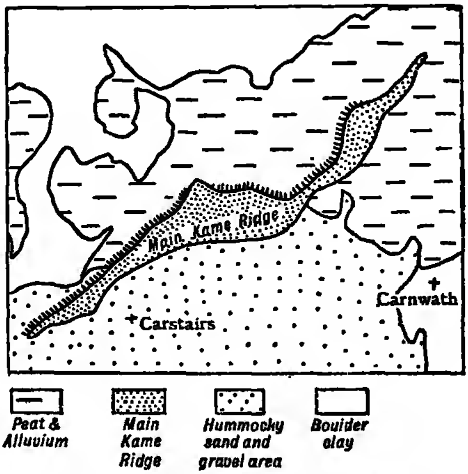


Fig. 246.—The Carstairs Kame.

It is evident that the ridge form of many kames and eskers causes them to simulate terminal or stadial moraines in their general characters. This is particularly so in the cases of kames, which follow the direction of the ice-front. It may be remarked, however, that the two types of accumulation differ widely in their actual constituents, a kame consisting of sand and gravel, while a moraine consists of unassorted rock-debris. Nevertheless, many terminal ridges might be placed on first inspection in either category (Fig. 243).

As already noted, terminal moraines do not invariably accompany the drifts of the Pleistocene ice-sheets. The southern limit of the drift in Britain is indeed free from such features, but farther north a discontinuous line of terminal moraines is traceable across Ireland and South Wales to the Vale of York. These occur near the margin of what is known in Britain as the Newer Drift, representing, it is believed,

a distinct later-glacial episode in which the ice did not extend so far into the plains. The existence of a terminal moraine in this case may be due to the fact that the ice-margin lay nearer the high ground, and consequently bore more material on its surface. On the other hand, terminal moraines of the older drift (p. 408) have been exposed for long periods to the obliterating effect of weather and water-erosion, and are known in many cases to have lost their continuity and freshness of form. A sheet of "newer drift" is also recognized in Germany, and some distance from its outer margin occurs the well-known Baltic End-Moraine, traceable from Denmark into West Prussia, a distance of over 600 miles, and following a course closely parallel with the Baltic coast (Fig. 262). On the outer, or "foreland," side are extensive plains of outwash gravels, while within it is a hummocky boulder-clay plain with innumerable small lakes. Farther north, as in Scania and the region of Oslo Fjord, there are other moraines marking pauses in the final northward retreat of the ice. Belonging to approximately the same stage of retreat is the great sand and gravel ridge which extends from east to west through Finland and is known as the Salpausselka. This has generally been interpreted as a terminal moraine, but its nature and relations suggest deposition in water, and it is not unlikely that it is, in part at least, a kame belt.

The "Lothian type" of glaciated lowland.—Finally we may briefly note the characteristics of what may be termed the "Lothian Type" of glaciated lowland. Throughout the central lowlands of Scotland, and particularly in the Lothians, isolated masses of igneous rock project through the sheet of "drumlinized drift" which mantles the plain, and reveal clear evidence of glacial erosion. Such masses often show the characteristic "onset and lee" effect, due to "plucking" (p. 367), modified in some instances by the accumulation of "tails" of boulder-clay in the lee of the obstacles. This highly characteristic "crag and tail" structure is well illustrated in Edinburgh, where the castle stands on the "crag" and High Street follows the sloping crest of the "tail" (Fig. 247). The Lothian landscapes, combining as they do the clearest evidence of both glacial erosion and deposition, present most spectacular witness to the landscape modifications wrought by the Ice Age.

Drainage modifications due to glaciation.—While in

many glaciated areas the broad features of the pre-glacial drainage have survived, local diversion of rivers is common. Where drainage has been established anew on the surface of a drift-sheet, we are dealing in reality with a special case of superimposition. In regions of low relief, such as Northern Essex, the whole surface was buried under boulder-clay, but the sub-drift valleys seem to have been marked by shallow depressions when the ice disappeared. As a consequence post-glacial erosion has followed the lines of pre- or inter-glacial drainage, and the valleys have been re-excavated in large part. Locally, however, in the same region we find valleys diverted by "drift plugs," as illustrated in Fig. 248. In such cases, post-glacial drainage has re-excavated a drift-filled valley except in one section, and we are left in doubt as to the precise cause of the diversion and of the date at which it became operative. Variations in the consistency of the drift or in the rate of melting of its interstitial ice must clearly be important. Elsewhere, post-glacial valleys completely disregard the

FIG. 247.—ACCUMULATION OF "TAIL" OF BOULDER CLAY IN LEE OF ROCK CRAG.

sub-drift surface, as in North-east Yorkshire (Fig. 249), where mining operations have sometimes revealed a neighbouring sub-drift valley, unmarked by any surface-feature. Where the drift-surface is hummocky with kame and esker ridges or terminal moraines, these may function as new water-partings, a phenomenon well illustrated by the Cromer moraine in Norfolk.

Despite the interest of such small-scale local phenomena, repeated in infinite variety over the glaciated lowlands, it must be recognized that the major hydrological influence of ice-sheets has been exerted through drainage diversions initiated *at the ice-margins*. Here large fresh-water lakes were formed, draining by channels, unrelated to the pre-glacial form of the country. These complex drainage phenomena passed away with the ice-sheets which brought them into being, but they left a residuum of lakes and diverted rivers, which are still important features of the landscape. Moreover, the former "marginal drainage" conditions can be reconstructed

by reference to a suite of highly distinctive landscape phenomena; the strand lines of the old lakes; the deltas built on their shores, and the steep-sided overflow channels by which their waters escaped.

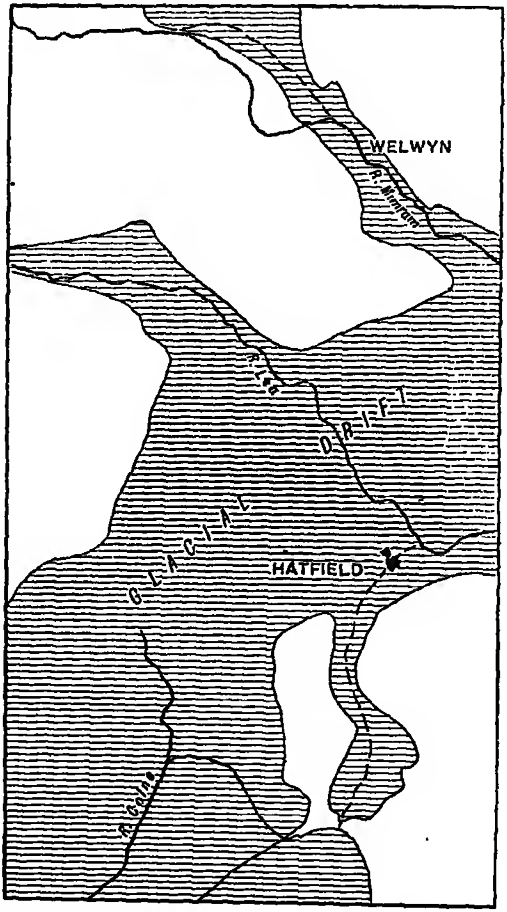
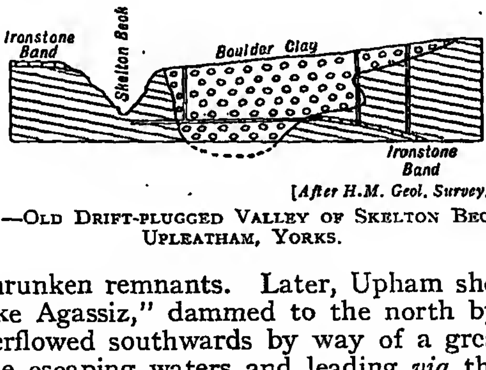


FIG. 248.—VALLEYS DIVERTED BY DRIFT-PLUGS IN HERTFORDSHIRE. Former courses of streams in dotted lines; drift area=shaded.

Existing ice-masses impound the natural drainage in various parts of the world. In the Alps the famous Märjelen See, dammed by the Aletsch Glacier, typifies the phenomenon on a very small scale, and similar lakes occur in Norway. The piedmont glaciers of Alaska

impound marginal waters on a much larger scale, and comparable effects have been studied at the ice-margin in Grinnell Land and the Nugsuak Peninsula in Greenland. We may distinguish cases in which the lake occupies the lower end of an ice-free valley, others in which it is ponded between the ice-front and rising ground, sometimes a morainic ridge, while in a few cases the lakes rest between two morainic ridges. The term "extra-morainic" has been proposed to cover all such lakes, but they are evidently not literally extra-morainic in every case, and the term "pro-glacial" is preferable.

It is evident that the great ice-sheets of the recent past must have given rise to similar, but larger, pro-glacial lakes, wherever they advanced against or across the lines of normal drainage. As long ago as 1823 Keating inferred the former presence in the Winnipeg depression of an extensive lake, of which Lake Winnipeg and its associates



[After H.M. Geol. Survey.

FIG. 249.—OLD DRIFT-PLUGGED VALLEY OF SKELTON BECK, NEAR UPLEATHAM, YORKS.

are the shrunken remnants. Later, Upham showed that this "Lake Agassiz," dammed to the north by the ice-sheet, overflowed southwards by way of a great trench, cut by the escaping waters and leading *via* the present Minnesota Valley to the Mississippi Valley at Fort Snelling. In Britain, the recognition of such phenomena was retarded by controversy as to the nature of the glacial drifts. Many preferred to regard the latter as accumulated on the sea-floor by the droppings of icebergs. If such were their origin there would be no possibility of ice-dammed lakes, the evidence for which was hence ignored by unseeing eyes. In 1863, however, Jamieson showed that the spectacular "parallel roads" of Glen Roy were lacustrine beaches arising at a time when Glen Roy and its neighbours were converted into lakes by an ice-front at their lower ends. All the principles which have guided more recent investigation of pro-glacial lakes are implicit in Jamieson's pioneer work. In the following chapter

[Photo by H.M. Geol. Survey. Crown copyright reserved.

FIG. 250.—THE PARALLEL ROADS OF GLEN ROY, INVERNESS.
View looking northwards up Glen Roy, showing "roads" (lake-terraces) at levels of 857, 1,068, and 1,149 ft. O.D. respectively (p. 393).

[Photo by A. J. Bull.

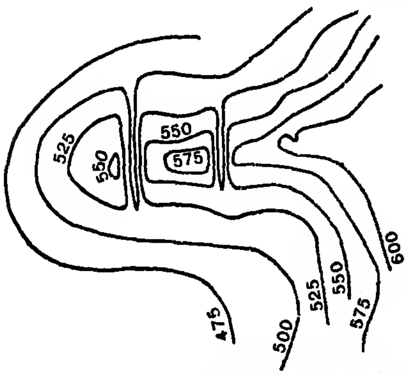
FIG. 251.—THE MÄRJELEN SEE, A SMALL LAKE DAMMED IN A TRIBUTARY VALLEY BY THE ALETSCH GLACIER, SEEN IN THE BACKGROUND (p. 392).

we shall pass in brief review some of the more important phenomena of this type since studied in Scandinavia and North America. We shall here illustrate the principles involved by reference to the classic work of Kendall in the Cleveland Hills of Yorkshire, for this work was the first to consolidate the general theory of pro-glacial drainage in this country.

Kendall followed the principle that it is rarely, if ever, safe to deduce the existence of a former pro-glacial lake, simply by reference to the form of the ground and the inferred position of the ice-front. The positive evidence for such lakes in the Cleveland Hills and elsewhere is of two types, geological (lake-deposits) and morphological (overflow channels). The floor deposits of existing pro-glacial lakes have been shown to reveal close laminations, corresponding with seasonal fluctuations in the volume and velocity of melt-waters. This same feature characterizes the deposits of the vanished Yorkshire lakes, as in the Vale of York (warp clays) and the upper part of the Esk Valley. Again, former water margins are marked by strand-lines, either actual beaches or small wave-cut shore scarps, and sand and gravel deltas have been built up at the mouths of streams draining to the lakes. Strand-lines are on the whole poorly represented in the Cleveland region, but well-marked deltas occur at several points. The accumulation of any of these deposits in recognizable bulk demands long life and stability in position for the lake. Moreover, they are easily destroyed by later erosion. Kendall laid more particular stress on the remarkable testimony of overflow channels, which, granted the requisite conditions, are more quickly produced than lake deposits and thus preserve a record of short-lived lakes.

The pre-glacial drainage plan of the Jurassic hill-country of Yorkshire comprised streams draining north and south from the main watershed of the North York Moors, the former flowing to the River Esk and the latter to the Pickering depression. A second main water-parting lay north of the Esk valley, separating streams draining to the sea from those draining to the Esk. In at least one stage of the Ice Age the central hilly country was invested by ice on all sides, while the higher parts were ice-free, projecting as " nunataks " above the ice-sheet. The ice-front dammed up a series of lakes in the marginal recesses

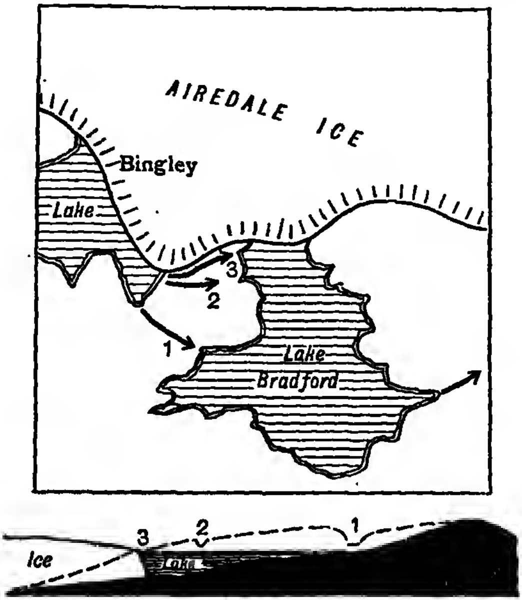
of the hills and in the larger interior valleys. These drained into one another by well-marked channels, now abandoned, in positions often quite unrelated to the drainage of the country. Kendall noted that the cross-sections of these channels resembled that of a railway cutting, with flat floor and steep sides. He associated this distinctive form with the rapid process of excavation by a large volume of quickly flowing water. It proved possible to recognize several distinct types and associations of channels on a basis of their topographic siting. *Direct overflows*, relatively few in number, carried the ponded waters across the main water-sheds, directly away from the ice (Fig. 256). *Lateral overflows* of two types were distinguished. In some cases these carried the drainage across spurs of the main water-shed, joining lakes in the minor valleys and giving rise to "severed spurs" (Fig. 252). In other cases the overflow took place along the margin of the ice by a channel cut partly in ice or moraine and partly in rock (Figs. 253, 255). If abandoned quickly these overflows are represented by one-sided shelves on the hill-sides, but many were deepened into rock-walled gorges. The lateral overflows occur in significant groups to which Kendall applied the terms "parallel sequence" and "aligned sequence." The former comprises repeated trenchings of the same spur by parallel overflows, produced by intermittent retreat of the ice-front to lower levels (Fig. 254). The intake level of each overflow is below that of the preceding (higher) member of the series, and it is evident that the channels were occupied successively, with a dropping water-level. An aligned sequence comprises the links between a series of lakes dammed in parallel valleys (Fig. 255). All the overflows have their fall in the same direction, representing continuous drainage along the main face of the hills. The lake levels in such a case would be successively lower along the series, till a main



[*After Kendall and Bailey.*

FIG. 252.—SPUR TRUNCATED BY OVERFLOW CHANNELS.
1·3 inches=400 feet.

escape was reached. The intake level of each overflow agrees with that of the outflow level (sometimes marked

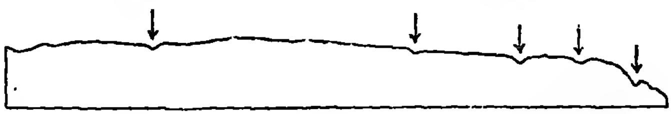


[After Wilson and Maufe.

FIG. 253.—MAP AND SECTION OF PRO-GLACIAL LAKES AND OVERFLOW CHANNELS IN AIREDALE.

by a delta) of the next channel upstream, since the two were linked by the lake level.

It is impossible without recourse to large-scale maps[1]



[After Kendall.

FIG. 254.—A PARALLEL SEQUENCE OF OVERFLOW CHANNELS, NEWLANDS DALE, YORKS.

1 inch=3,500 feet (horizontal), 1,750 feet (vertical).

to follow in detail Kendall's reconstruction of the Cleveland overflows, but the main features are shown in Fig. 256. The ice overrode the northern watershed as far west as Roxby High Moor. West of that point a series of lakes

[1] Reference may be made to sheet 7 of the Ordnance Survey Half Inch Map, which shows the general physiography of the area clearly.

was impounded along the northern face of the hills, draining to one another by lateral channels, and eventually discharging across the ridge into Lake Eskdale by direct overflows. Lake Eskdale (continued in Lake Kildale) was dammed by ice at both eastern and western ends, the former ice-front in the east being marked by a conspicuous moraine, spanning the Esk Valley at Lealholm. At its maximum stage the level of Lake Eskdale was at 715 feet O.D., and it discharged eastwards into smaller lakes held up in the southern tributary dales. As far as Lake Glaisdale the fall in level was slight; thence the water passed by a well-marked channel across a high-level spur

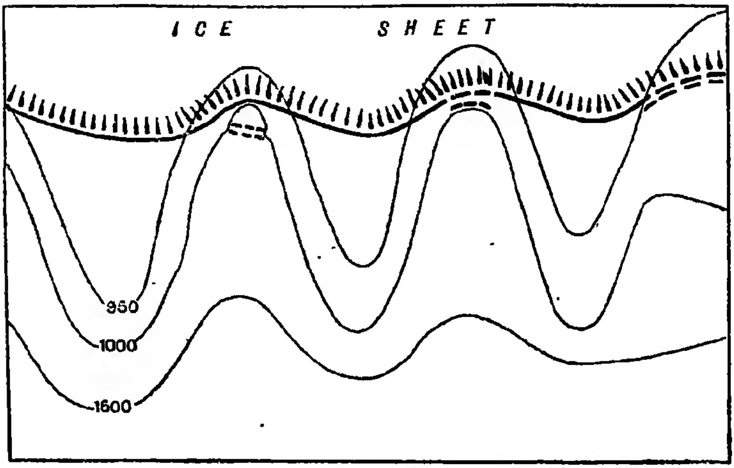
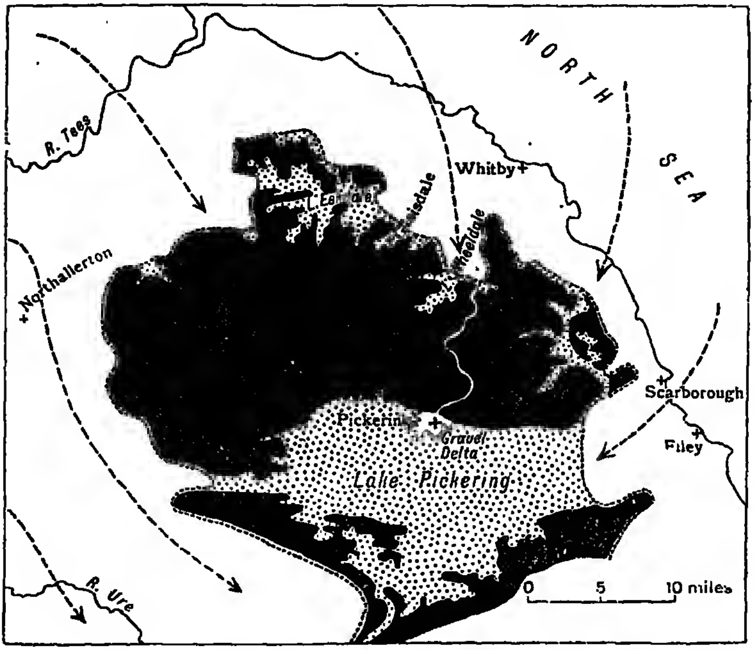


FIG. 255.—AN ALIGNED SEQUENCE OF OVERFLOW CHANNELS.

to Lake Wheeldale (670 feet O.D.) and thence by a marginal channel to a small lake near Goathland (Fig. 256). From here the great direct overflow of Newton Dale, perhaps the most spectacular of its kind in Britain, led across the watershed to Lake Pickering (225 feet O.D.). Its outfall is marked by the large gravel delta underlying the town of Pickering. A similar intercommunicating series of lakes existed along the eastern margin of the area and discharged similarly into Lake Pickering. The latter occupied the great pre-glacial depression on the Kimmeridge Clay, intervening between the Jurassic hills and the Chalk Wolds. This depression was originally drained eastwards to the sea by the River Derwent. Later the ice-front blocked this

depression at both ends, and outflow was established by the famous Kirkham Abbey gorge, which enters the Vale of York, south of the well-known terminal moraines which mark the limit of the ice. Kendall inferred that this southern portion of the Vale of York was also occupied by a lake, and later work has fully established this conclusion (Fig. 257). The Derwent drainage still finds outlet by the Kirkham gorge, and this major diversion of



[After Kendall.

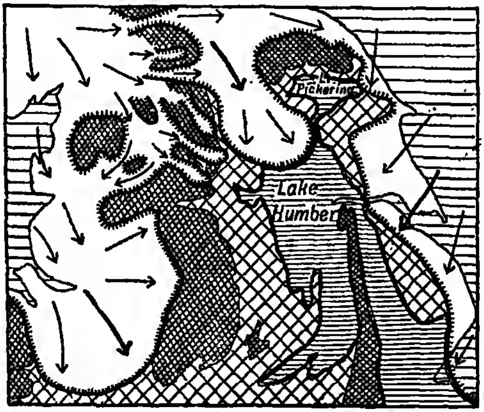
FIG. 256.—THE PRO-GLACIAL DRAINAGE OF N.E. YORKSHIRE.

Pro-glacial lakes = dotted; ice-free ground = black; ice-sheet = white; directions of advance shown by arrows.

drainage survives as a permanent legacy of the pro-glacial conditions.

The phenomena described above correspond with the maximum extension of the ice of the "Newer Drift" (p. 408). Younger channels at lower levels, corresponding to a stage in the retreat of the ice, can also be traced in the area, while there are not wanting signs of much older, partly obliterated, channels referable to an earlier glaciation.

Despite Kendall's lucid and almost unanswerable demonstration of the character of the Cleveland overflow channels, attempts have been made to explain away individual cases as products of "normal" drainage evolution. The motivation of these arguments is hardly in doubt; they represented an attack on the land-ice theory. As Kendall justly remarked, acceptance of the overflow channels gave "the merciful and much needed *coup de grâce* to the Great Submergence" (p. 393). To-day, however, the case for Kendall's interpretation rests not only on the Cleveland channels but on identical phenomena described from the Pennine flanks, the Lake District, Southern Scotland and many other regions.

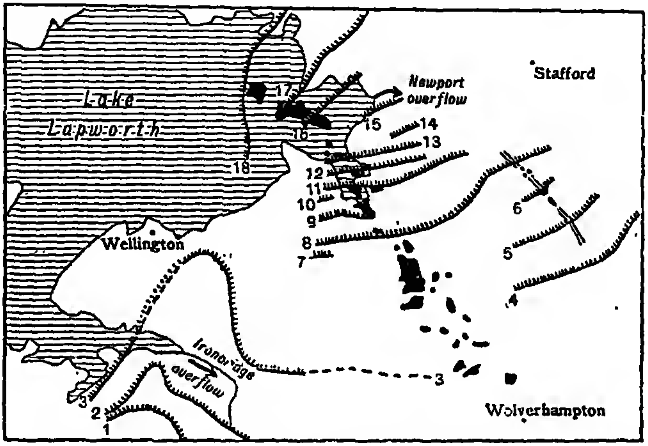


[*After Raistrick.*

FIG. 257.—A LATE STAGE IN THE GLACIATION OF NORTHERN ENGLAND.

Everywhere the channels are, with few exceptions, drift-free, though sometimes cut in the drift, and they consistently show a fall towards the ice-free country. We cannot, however, yet envisage in detail the whole system of pro-glacial drainage in Britain; much work remains to be done. The possibilities of the subject are indicated by Kendall's statement that "one may start from Edinburgh and follow a continuous succession of channels (not, however, all of the same period), all sloping in line of route, almost to the Wash." He suspected that at one stage the general southerly outflow passed, by way of the Little Ouse–Waveney depression in Norfolk, to the southern North Sea, and that the "final release of the East Coast drainage must have been by way of the Straits of Dover."

In the west, it has been shown that a major diversion of the Severn drainage was initiated by pro-glacial overflow. The Cheshire–North Shropshire Plain is almost surrounded by ground exceeding 300 feet in height, and the pre-glacial Upper Severn drained northwards to the Dee estuary. During the retreat of the ice from this great embayment, pro-glacial lakes were formed and overflows established across the bounding rim near Ironbridge and Newport, Salop. With further retreat the Newport outlet was abandoned, the whole outflow of the growing lake (Lake Lapworth) passing *via* Ironbridge to the Lower Severn



[*After* L. J. Wills and H.M. Geol. Survey.

FIG. 258.—THE RETREAT OF THE ICE IN THE WOLVERHAMPTON DISTRICT. Successive ice-stands numbered. Esker-trains in black. Sub-glacial channel shown crossing stands 5, 6 and 8.

basin and cutting the deep Ironbridge gorge through the former watershed (Fig. 258). This diversion ranks with that of the Derwent as one of the major glacial modifications of the British drainage system.

It should be noted that where, as in the cases of the Derwent and Severn, overflow lines have survived as existing river outlets across major or minor watersheds, the effects simulate those produced by normal water-gaps in the scarplands, or by "epigenetic gorges" through ridges, due to superimposition of drainage. Each case, therefore, demands consideration on its merits, and glacial diversion cannot be fairly invoked without the full series of supporting evidences. Thus the Witham at Lincoln

and the Thames at Goring breach uplands bounding extensive depressions. It is not difficult to envisage the latter as former lakes, and it has, in fact, been suggested that Goring Gap was initiated by the overflow of a suppositious "Lake Oxford," thus uniting the Upper and Lower Thames drainage. The hypothesis remains worthy of investigation but presents many difficulties. It is essential, above all, to realize that there is no need to invoke pro-glacial drainage to explain every such case.

Nivation.—We cannot exclude from the general field of glaciation certain important ancillary processes grouped under the head of "nivation." Nivation is the work of snow and frost beyond the true glacial limits. It may be studied to-day in regions which show a fluctuating or seasonal snow cover—the sub-arctic islands, the tundras, and mountain regions devoid of a permanent snow cover.

The direct action of nivation is best seen in the formation of "snow niches," shallow amphitheatres occupied during part of the year by a small snow patch. Such patches tend to collect originally in some faint hollow, and there is no doubt that they slowly "dig themselves in." The nature of the process can be gathered by examination of the snow margins during the mid-day hours at any period of the year, but particularly in the general thaw of spring or early summer. At these times the marginal zone is bare of vegetation and is saturated with water, while the ground farther from the edge is often completely dry. During the night-frosts the rock of the marginal zone is shattered and comminuted by the freezing of interstitial water. It is then slowly removed by the wash of the melt-water, and by "sludging" or soil creep (see below). The co-operation of wind in removing the material, when dry, is probably also important. Since, in the course of seasonal melting, the snow margin slowly retreats, marginal shattering is brought to bear on all parts of the floor, and the depression grows as a whole. Snow niches of this kind may be found all over the higher parts of the pasture zone in the Alps. They present a striking appearance and would seem to defy explanation by any but the above hypothesis.

Effects of even greater aggregate importance arise through the process of solifluction. The melting of a thin snow cover, and of the upper parts of the ground beneath, leaves a thin layer of saturated material superimposed on a thicker underlying frozen mass. Over the surface of the

latter the surface layer creeps or flows, where the surface slope is sufficient, and by a long continuation of this process slopes are steepened and great accumulations of "sludge" formed on the lower ground. Graphic descriptions of the downhill creep of such snow-bog in Spitzbergen have been given by Sir Martin Conway. The sub-surface frozen layer is a familiar feature in Swedish Lapland, where it is known by the name of *tjäle*. It is impervious and arrests the downward penetration of water, thus assisting the lubrication of the overlying mass. Solifluction above a "tjäle layer" is a process linked, by many intermediate stages, with ordinary scree-formation under the influence of frost. The "stone-rivers" of the Falkland Islands and the rock-glaciers of Alaska—in reality long trails of scree descending the valley—were certainly initiated under conditions of nivation, whereby alternate freezing and thawing actuated the moving mass.[1]

While it is evident that nivation still in progress is an important fact in the physical geography of the earth, it must have been of even greater importance in the past. In each of the glacial periods, it began before the true ice-sheets were formed, extended beyond their widest limits, and persisted during and long after their retreat. Early nivation niches no doubt began the sculpture of the glaciated mountain ranges, representing the earliest stage of corrie-glaciers in many cases. Further, we should expect to find the results of nivation processes engraved in the extra-glacial tracts, a hypothesis fully borne out in Southern Britain. The "Head" of South-west England is a rubble-drift made of local rocks, mantling the slopes and filling the valley-bottoms. It must have originated under conditions resembling those of the sub-arctic regions to-day, when snowfields occupied the higher ground. The "Coombe-Rock" of South-east England is a similar and widely distributed Chalk rubble, sometimes disposed in flat low fans at the foot of steep Chalk slopes. Further, it is a striking fact that in many parts of Southern

[1] Though solifluction and kindred processes are favoured under conditions of nivation, they extend to-day into regions where frost and snow play no large part in the processes. Wet clay slopes in temperate climates are subject to appreciable downhill creep. The sides of trenches excavated on clay slopes around North London during the Great War and lined with wire-netting, bulged inwards till the sides met. Under extreme conditions minor landslips occur in such situations. The great landslips on the deeply weathered slopes of the humid tropics (p. 182) may also be grouped under the general heading of solifluction.

England southward facing slopes are exceptionally steep, where no structural explanation of the fact is forthcoming. Such slopes faced the sun, and on them thaw phenomena and solifluction may well have been facilitated.

It seems justifiable to include under the heading of nivation the excavation of channels by snow-melt waters. No contemporary examples of the phenomenon have been described; it doubtless requires rapid melting of large snowfields. In the Chalk country of England, however; there exist remarkable dry channels, of which the famous Devil's Dyke near Brighton may serve as type. These channels, draining in most cases from the face of the Chalk excarpments, differ from normal dry chalk valleys in having abrupt heads, steep sides, and flat floors. Their cross-section, indeed, is very similar to that of "overflow channels," and they show the same signs of having been excavated by a large mass of rapidly moving water. They have been regarded as in some obscure sense "glacial," but since they extend into regions in which the presence of true ice-sheets cannot possibly be invoked, it seems most in accord with the facts to attribute them to the melting of snow-caps on the Chalk Downs (Fig. 178).

CHAPTER XXIII

"GLACIAL CONTROL" IN THE PHYSICAL GEOGRAPHY OF THE EARTH

General.—The direct effects of glaciation in erosion, deposition and drainage modification have been great, but a study of these effects does not exhaust the interest of the Pleistocene Epoch for the geomorphologist. The period embraces also fluctuations of sea-level and river-action, and large changes of climate in regions far removed from the ice-masses. Marine erosion, river erosion, and even desert erosion have performed the latest stages of their work under a general "glacial control," and the accumulation of ice-masses deformed the crust. Accordingly the Pleistocene Epoch, the last and shortest of the recognized geological time-divisions, is of crucial importance to the geomorphologist. We may, therefore, attempt to assess its general contribution to the physical geography of the world, and, in order to do so, it is necessary briefly to review the conclusions of geologists as to the character and duration of the Ice Age. Despite its comparative brevity and the insignificant thickness of its deposits the Pleistocene Epoch has yielded to close study a story of amazing complexity. The literature of the subject is vast and, in part, controversial, but there is essential unanimity on the aspects of the subject which here concern us most.

As already noted, the normal condition of the planet during the geological past has been "non-glacial," though glacial episodes comparable with the Pleistocene glaciation have occurred more than once. In Middle Tertiary (Miocene) times the earth appears to have been essentially ice-free. Thereafter we find evidence of progressive refrigeration leading up to the Ice Age. The existing considerable ice-masses show that the glacial condition has not yet passed away. These ice-masses constitute an invaluable standard of comparison in investigating the record of Pleistocene times. They represent water temporarily withheld from the oceans. Their computed areas and thicknesses represent a water-volume of 18 million cubic kilometres, equivalent to a layer 50 metres thick spread over the existing oceans.

The character and duration of the Ice Age.—Study of the glacial drifts in both Europe and America has clearly established the existence of multiple glaciation—*i.e.* of distinct glacial episodes, separated by warm interglacial intervals.

The Scottish geologist James Geikie was the first strongly to urge this conclusion, and the facts on which he relied are fully set forth in the last (1894) edition of his "Great Ice Age." His conclusions were received with considerable scepticism in many quarters, but were triumphantly vindicated by the publication in 1909 of the researches of Penck and Brückner in the Alps.

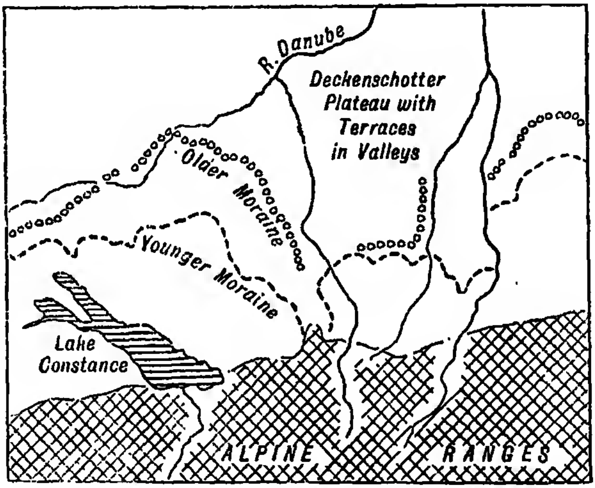
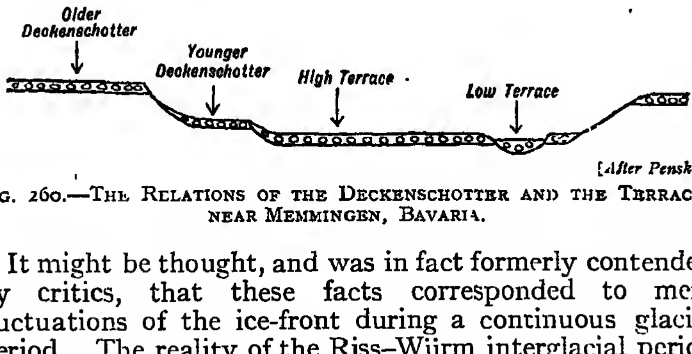


FIG. 259.—THE OLDER AND THE YOUNGER MORAINE IN THE ALPINE FORELAND.

The Alpine Foreland shows two distinct moraines: the Young Moraine, which retains its form essentially uneroded and is composed of little-weathered material, and the Old Moraine, deeply weathered and with its form largely obliterated (Fig. 259). Confirming and extending these indications, the valleys draining away from the Alps show four series of outwash gravels, at different heights above the stream courses, the Older Deckenschotter, the Younger Deckenschotter, the High Terrace Gravels, and the Low Terrace Gravels. The Older Deckenschotter were spread out in great sheets on the low ground of the Foreland; the Younger Deckenschotter rest in depressions cut through the older sheet; while the Terrace Gravels, High and Low,

at still lower levels, follow the courses of the present streams (Fig. 260). When these gravels are traced towards the glaciated area each proves to be associated with a moraine stage, the Low Terrace with the Young Moraine, the High Terrace and Younger Deckenschotter with the Old Moraine, itself in reality a "double" feature. The moraines associated with the Older Deckenschotter are poorly preserved, but can be definitely identified in some cases. The older gravel spreads, like the older moraines, are more deeply weathered than their younger analogues, and where two of the gravel spreads are locally superimposed, a distinct weathered surface, and sometimes an intervening layer of loess, separates them. Similar relations can be demonstrated in Switzerland, France, and Italy. On this basis Penck and Brückner deduced four distinct and successive glaciations: named, respectively, the Günz, Mindel, Riss, and Würm glaciations, separated by interglacial periods.



[After Penck.

FIG. 260.—THE RELATIONS OF THE DECKENSCHOTTER AND THE TERRACES NEAR MEMMINGEN, BAVARIA.

It might be thought, and was in fact formerly contended by critics, that these facts corresponded to mere fluctuations of the ice-front during a continuous glacial period. The reality of the Riss–Würm interglacial period is, however, attested by lacustrine and other deposits which yield remains of plants and mammalia signifying a climate warmer than at present, and there are abundant indications that the preceding Mindel–Riss interglacial period was even warmer and longer. It cannot be proved that ice and snow completely disappeared from the higher mountains in these warmer intervals, though this is very probable. The general tenor of the evidence suggests that the Mindel–Riss interglacial period witnessed the most complete deglaciation of the region; that maximum glaciation was achieved at the Riss stage; and that the Günz glaciation was comparatively limited, involving snowfields and glaciers not greatly exceeding those of the present day.

Investigations in other regions have amply confirmed the type of glacial sequence deduced in the Alps, and in several cases reveal a succession of events closely similar in detail. A broad distinction between an "older" and a "newer" drift is widely in evidence. Thus, in Britain, while the older drift extends southward to the line of the Bristol Channel and the Thames Valley in a much dissected sheet, devoid of well-marked surface forms or terminal moraine, the "newer" drift terminates at a line farther north (Fig. 261) which is marked by terminal moraines, as in the Vale of York.[1] In North Germany and Poland similar relations can be made out in more detail. Four moraines, known by the names of Elster, Saale, Flaming, and Weichsel, are traceable in Germany and continue into Poland. A pre-Elster stage (the Elbe) is also more obscurely represented. Correlation with the Alpine stages has been essayed as shown in Fig. 262, both the more northerly moraines being tentatively assigned to the last (Würm) glaciation. A similar succession constituting in order of age the Nebraskan, Kansan, Illinoian, and Iowan–Wisconsin glaciations has been made out in North America. Multiple glaciation, not yet studied in detail, is evidenced in China, the Himalayas, South America, and New South Wales.

FIG. 261.—APPROXIMATE LIMITS OF THE OLDER AND NEWER DRIFTS IN GREAT BRITAIN.

There is considerable concurrence of evidence tending to the important conclusion that the main glacial and interglacial stages were broadly contemporary throughout the world. Rigid proof is of necessity lacking, yet the convergence of many lines of argument goes far to produce conviction. In the first place it should be noted that there is no *a priori* improbability in the idea. The prime cause of glaciation is still a matter of doubt and controversy, but it was certainly general and not local. It is signi-

[1] Recent work in East Anglia has demonstrated the existence of four distinct boulder-clays, which cannot, however, at present be satisfactorily correlated with the Alpine and Northern European glacial stages (see J. S. Solomon, *Proc. Geol. Assoc.*, XLIII (1932.)

ficant that existing ice-masses show some evidence of sympathetic behaviour over wide areas. There has been simultaneous shrinkage, during the last century, of glaciers in Greenland, Antarctica, Scandinavia, the Alps, the Himalayas, the Andes, and other regions. This has certain force as an analogy, but would not take us far without supporting evidence. Such evidence is to hand in the comparable degree of weathering and dissection of deposits occupying the same relative position in the local glacial sequences of the Alps, Northern Europe, and North America. An argument still more cogent depends on the general similarity of widely separated glacial successions already noted.

To make comparisons we must have regard not merely to

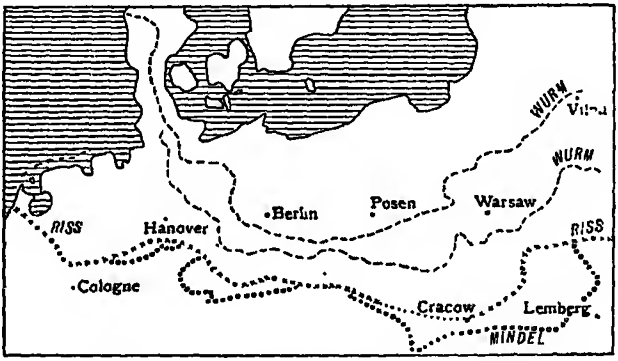


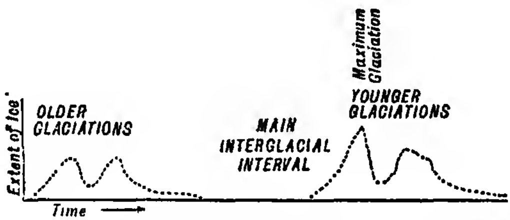
FIG. 262.—TERMINAL MORAINES OF THE NORTH EUROPEAN PLAIN.

the number but to the intensity and duration of the successive episodes. Basing his calculation on degree of weathering, Penck concluded that in the Alps the relative lengths of the three interglacial periods and of post-Würm time were as follows: Günz–Mindel, 3; Mindel–Riss, 12: Riss-Würm, 3; post-Würm, 1. The essential fact is the preponderant length of the Mindel–Riss interglacial stage, which implies a virtual bi-partition of the Glacial period, graphically illustrated by Heim (Fig. 263); that is to say, there were two phases of cold, an older and a younger, each subdivided by a short interglacial episode, which may not have involved complete disappearance of ice from the heights, but separated from one another by a long ice-free period. It is not surprising that the North European drift reveals a similar record of spacing and intensity, but it can hardly be without significance that North America tells the

same story. Here the Kansan–Illinoian interval (the Yarmouth interglacial period) is the major one of the series, and a curve drawn for the North American glaciation would closely imitate Fig. 263. Similar evidence is to hand from the extraglacial regions, there being many indications that the glacial phases in high latitudes were contemporary with pluvial phases of high rainfall nearer the equator. The fluctuating rainfall is recorded in the strand-lines of now vanished or shrunken lakes, and from widely separated areas comes the testimony of *two* main high-water levels.

Further argument in favour of world-wide sympathetic variations in glacial climates derives from the closely similar histories of retreat of the last ice-sheets, Würm and Wisconsin respectively, in the Scandinavian and North American regions (pp. 413, 416).

Before leaving the chronological aspects of the Ice Age we may note that reasoned estimates of the absolute



[*After Heim.*

FIG. 263.—RELATIVE INTENSITY AND DURATION OF THE GLACIAL EPISODES IN THE ALPS.

duration of the period and its stages are obtainable. The remarkable researches of De Geer and his followers in Scandinavia have shown that sediments with a well-marked seasonal layering accumulated in waters, both fresh and salt, beyond the ice-edge during the last great retreat. Alternating coarse and fine layers occur, and De Geer assumed that the former represented summer melting, while the latter represented the less active sedimentation of the winter season. By the counting of these layers in carefully correlated sections over a wide area he produced his famous geochronology of Late Glacial times. On this basis it is estimated that the last Fenno-Scandian ice-sheet began its retreat from the North German Plain some 25,000 years ago, and that the retreat lasted 16,000 years until, 9,000 years ago, the last remnants of the sheet were left on the Swedish uplands near Lake Ragunda. Such figures cannot, of course, be precisely

accurate, but no one has doubted that they are reasonable approximations to the truth. If we assume that the growth of the ice-sheet took about the same time as its dispersal and recall, further, the relative durations of the interglacial intervals (p. 409) it will be seen that 1,000,000 years is a reasonable estimate for the total duration of the Glacial period, as a whole.

The foregoing brief summary of the " chronological structure " of the Glacial period is a necessary preliminary to a description of some of its major physiographic effects. We see that in a period of about 1 million years there have been four cycles of growth and dispersal of ice-sheets. It is apparent that the later glaciations must have undone or obscured much of the work of their predecessors. In Europe it is generally held that the Riss was the maximum glaciation, its limits extending beyond those of the Würm, save locally. But the last (Würm) glaciation is accountable for a large proportion of the more spectacular effects in erosion and deposition, both in the mountains and the piedmont plains. Since the last ice-sheet has left clear stratigraphical and physiographic evidences, which have been intensively studied in both Europe and America, it becomes the comparator for the older glaciations, which must in their turn have produced similar effects.

Some Major Physiographic Effects of the Ice Age

The physiographic changes accompanying glaciation are largely bound up with changes in the relative level of land and sea, incidental to the growth and dispersal of the ice-sheets. Such changes were complex in their causation, being due to the simultaneous operation of several factors. They affected not only the vicinity of the ice-sheets, but in some degree the whole earth. Let us consider the first and simplest of the processes tending to change of base-level. We have already noted that existing ice-masses represent the removal of a layer of water, 50 metres thick, from the oceans. Our growing knowledge of the extent and probable thickness of the Pleistocene ice-sheets enables similar calculations to be made. It is estimated that the last glacial cycle (Würm) represented the abstraction and return to the ocean of over 34,000,000 cu. km. of water, equivalent to a layer 85 metres in thickness. The corresponding figures for the maximum

glaciation (Riss) are 42,000,000 cu. km. and 105 metres. Even if these figures were entirely correct, to apply them literally would involve the too artificial assumption of exact contemporaneity of formation and melting all over the world. This cannot be predicated, and Daly considers it better to adopt slightly smaller figures, 75 metres and 90 metres, as representing the probable actual shift of sea-level associated with the glaciations in question. Even so, we are confronted with the inescapable fact of eustatic shifts of sea-level of large dimensions. If it could be assumed that the lands remained fixed and stable during the waxing and waning of the oceans, such eustatic shifts would be equal in amount everywhere. Such assumption is implicit in the writings of some workers, but it can be justified neither on grounds of theory nor observation. The formation of ice-sheets involves an appreciable shifting of the pre-existing distribution of load on the surface of the earth, namely, the addition of an ice-load to a relatively limited tract and the subtraction of an equal load from the more extensive ocean surfaces. To this shift of load the earth must respond in accordance with the principles of isostasy explained in Chapter III.

It was, in fact, deduced by Jamieson as long ago as 1865, long before the formal enunciation of the Theory of Isostasy, that the land sank beneath the added weight of an ice-cap, and recovered during, or after, the melting. Such a conclusion could quite fittingly be deduced from our present knowledge of geophysics, but in any case it is amply borne out by observation in and around the glaciated centres. Further, in accordance with isostasy the depression of the ice-loaded tracts must involve outward movement of material in depth. Opinions differ as to the effect of such outward movement; it might lead to a strong, more or less localized, uplift of the peripheral tract, or to smaller effects spread over a larger area. In general, it is true to say that the whole planet must tend to become adjusted isostatically to localized ice-loads, so that we cannot, on theoretical grounds set any limit of distance to the land-movements resulting.

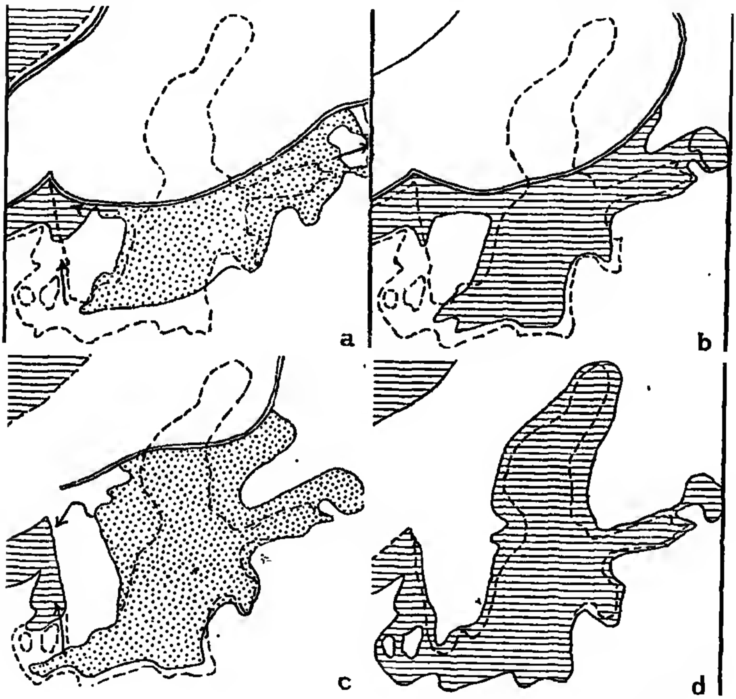
The eustatic oscillation of sea-level and the isostatic oscillation of the ice-loaded tracts and its associated movements were no doubt the chief factors involved in Pleistocene changes of level. Two other effects remain to be noted, however. First, isostatic adjustment took a considerable time for completion, but Daly envisages an

immediate elastic response to loading (and de-loading), affecting not merely the glaciated tracts but the whole earth. The calculated effect is relatively small and becomes added in effect to the isostatic changes of level. Secondly, there may have been temporary distortion of the sea-level surface in accordance with excesses or deficits of mass in the glaciated areas. If the ice-sheets had been supported by a rigid crust, without isostatic adjustment, the sea-level would have been "attracted up" towards the ice-mass to a definite and calculable extent. This certainly gives no picture of the true conditions, but *until isostatic adjustment was complete* this effect must have operated, and in any event, temporary excess of mass during the growth of the ice-sheets must have tended to raise sea-level in the vicinity, and temporary deficit during melting to depress sea-level.

The foregoing paragraphs indicate the great complexity of the problems of Pleistocene changes of level, and it is well to distinguish clearly the roles of theory and observation in the matter. Our knowledge of geophysics might enable us to deduce the above effects and calculate the magnitude of some of them, but we cannot yet approach the problem of the rate and extent of isostatic or elastic deformation by deductive means. Our conclusion on these points must depend on the facts of observation—a reconstruction, as detailed as possible, of what *did* happen during the Ice Age. It will be seen, therefore, that a careful study of Pleistocene earth-movements is calculated to throw much light on the condition of the earth's interior. As Daly has contended, the formations and dispersals of the ice-masses were, for the geophysicist, major experiments whose results are crucial in the general study of earth-movement. We cannot here pursue this interesting aspect of the question, nor is investigation sufficiently advanced to afford other than tentative conclusions. Our present concern is with the effect of the Pleistocene movements on the present configuration of the earth.

The Baltic region.—The terminal moraine of the last Scandinavian ice-sheet traverses the Danish Peninsula from north to south, and then loops eastwards, south of Berlin and Posen, to the neighbourhood of Vilna (Fig. 262). The retreat from this line began, as we noted, some 25,000 years ago, and the retreat was punctuated by pauses, marked by well-developed stadial moraines. We have thus the Pomeranian Moraine, the Scanian Moraine

(13,700 B.C.) and the Salpausselka of Finland, with its continuation crossing Southern Sweden in the latitude of Stockholm (10,200 B.C.). During the retreat to the last-named line, a large part of the present Baltic area was occupied by a vast pro-glacial lake—the Baltic Ice Lake, separated from the sea by a land-bridge linking Denmark with Sweden (Fig. 264*a*). The surface of this lake was



[*After Daly.*

FIG. 264.—STAGES IN THE EVOLUTION OF THE BALTIC SEA.

(*a*) The Baltic Ice Lake. (*b*) The Yoldia Sea. (*c*) The Ancylus Lake. (*d*) The Littorina Sea.

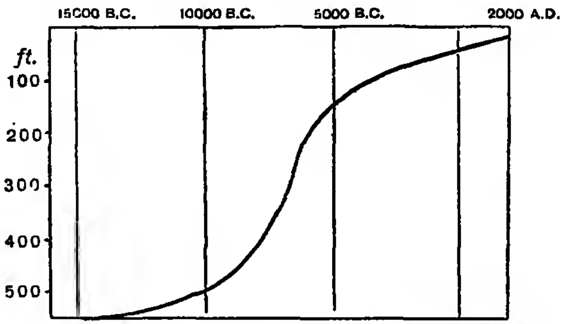
Boundary of the ice-sheet=double line; fresh water=dotted; salt water=horizontal shading; overflows shown by arrows.

above sea-level, and it drained to the sea by successive overflows, a direct overflow in the neighbourhood of Copenhagen, a marginal overflow across the lake region of Sweden, a direct northward overflow *via* Lake Ladoga to the Arctic Sea, while finally, with a rising sea-level, communication with the ocean was established across the region of the "lake belt." Next, the Baltic Basin was

flooded with salt water—the stage of the Yoldia Sea (Fig. 264*b*). There is clear evidence that at this stage the sea was rising faster than the land, and submergence, following retreat of the ice, was progressive. The Yoldia Sea persisted for some 500 years, but by 7,000 B.C. the recoil of the land from glacial loading in the south closed the outlet in Southern Sweden, and the Ancylus Lake was formed. This lasted for nearly 3,000 years, draining first *via* the " lake belt route," and latterly by the " Copenhagen route." The latter may well have been opened by reason of depression in the former peripheral tract and a continuation of such movement, coupled with a still rising sea-level, brought about renewed flooding of the Baltic Basin—the stage of the Littorina Sea (Fig. 264*d*). A continuance of crustal recoil has led to a shrinking and shallowing of the waters to their present condition.

The successive water-bodies noted above engraved recognizable strand-lines around the Baltic Basin, and their floor deposits can be recognized and separated, in large part, by their included fossil shells. There are contemporary strand-lines and marine deposits on the Norwegian littoral. A study of the existing elevations of these strand-lines and deposits throws much light on the character and rate of isostatic recovery and on its fluctuating contest with rising sea-level. For all four stages, it is true that the strand-line and deposits in the Baltic Basin rise from south-east to north-west, *i.e.* as traced towards the centre of former ice dispersal over the Gulf of Bothnia. The same is true on the open sea-coast of Norway, where the deposits rise in a south-easterly direction. In the offshore islands the strand-lines show little warping, but they rise steeply inland. These facts can be rendered clear by drawing isobases (p. 56) through contemporary deposits now at the same height. Isobases drawn for the late glacial water-laid deposits as a whole give an aggregate picture of the isostatic recovery (Fig. 15), and show that the total uplift increases in all directions towards a centre on the western shore of the Gulf of Bothnia. This makes clear the character and total extent of the movement; but consideration of the isobases for the four successive stages throws light on the rate of movement and demonstrates that the main recoil was considerably retarded. Thus the Littorina beaches were formed after the greater part of the melting was complete, yet they rise over 90 metres as traced from the Southern Baltic shore to the centre

of uplift. We conclude therefore that a large amount of the total uplift was deferred until melting was nearly complete. Further, since the strand-line gradients for the Baltic Ice Lake and the Yoldia Sea are closely comparable, we infer that little recovery took place in pre-Yoldia times ; the tilting of both sets of deposits took place during and after the Yoldia Stage. There is also clear evidence that the recoil is not yet complete, for the analysis of tide gauge records reveals continuing uplift, reaching a maximum rate of 11 mm. per annum at the head of the Gulf of Bothnia and diminishing to zero in the south-eastern coastal regions of the Baltic Sea. Though there is still room for difference of opinion in the interpretation of the details of this complex history of



[*After Nansen.*

FIG. 265.—CURVE SHOWING PROGRESS OF UPLIFT (IN METRES) OF THE CENTRAL PART OF THE FENNO-SCANDIAN REGION, DURING AND SINCE THE RETREAT OF THE LAST ICE-CAP.

uplift, a curve constructed by Nansen (Fig. 265) demonstrates the main facts. It will be seen that the maximum rate of uplift occurred during the Yoldia and Ancylus periods, and that it was preceded and followed by lengthy periods of slower movement.

The Great Lakes of North America.—The retreat of the last great North American ice-sheet has been shown by Antevs to have followed a chronology closely comparable with that deduced in Scandinavia. The details of such comparison need not here concern us, but it must be noted that the geographical contributions of the retreat are hardly less notable than in the Baltic region.

The basins in which lie the Great Lakes of North America are in large measure of pre-glacial fashioning, though in the nature of the case their precise pre-glacial

history is difficult to decipher. It is clear, however, that depressions, either pre-glacial or formed during the glacial advance, controlled the form of the retreating ice-lobes of the last great ice-sheet of the region. At its maximum extension the Wisconsin ice-sheet extended well beyond the Great Lakes depression, as far south as the neighbourhood of Cincinnati.. In the initial stages of retreat the melt-waters from the ice edge escaped without hindrance into the Ohio and Mississippi Basins, but thereafter a complex series of changes ensued, illustrated in Figs. 266 and 267.

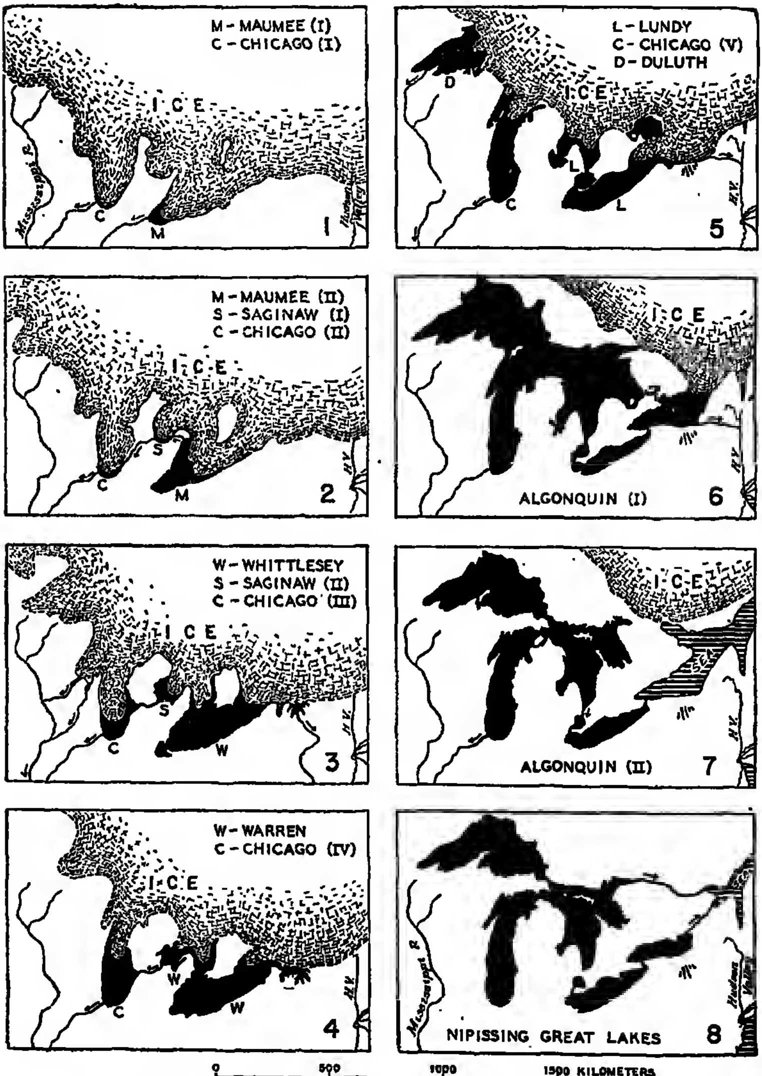
The first clearly decipherable stage in the retreat is marked by the uncovering of the south-western end of the Lake Erie depression. Here a pro-glacial lake—Lake Maumee—formed between the lobate ice-front and an abandoned stadial moraine. In an early stage, this discharged by direct overflow near Fort Wayne along the line of the present Wabash River to the Mississippi Basin. At a later stage, when the lake was enlarged by further retreat, a lower-level outlet was opened, permitting lateral drainage into the lake in front of the neighbouring Saginaw ice-lobe, which, in turn, discharged laterally *via* Imlay and Grand Rapids to Lake Chicago—the lineal ancestor of Lake Michigan. Here direct southerly outflow was achieved along the line of the present Illinois River.

In the next stage of ice withdrawal a much larger water body—Lake Whittlesey—succeeded Lake Maumee in the Erie Basin, and there is evidence of a temporary flow eastwards along the ice-front, and thence southwards across New York State. A slight readvance of the ice re-established western overflow, however, but the Imlay channel was abandoned, the overflow passing marginally *via* Ubly to Lake Saginaw and thence *via* the Chicago route.

In the next or Lake Warren Stage this régime, became further established, the enlarged water body embracing the former Saginaw Lake and extending eastwards into the Finger Lake region. Lake Chicago had become much enlarged, occupying the southern half of the Michigan Basin. There followed the uncovering of the western end of the Superior Basin, where Lake Duluth formed, and a further enlargement of Lake Chicago. Both these lakes drained by direct overflow to the Mississippi.

The eastern water body—Lake Lundy—successor to

Lake Warren, drained eastwards by an overflow at Syracuse to the Mohawk Valley, and hence to the Hudson



[*By permission from Daly's "The Changing World of the Ice Age," Yale Univ. Press.*

FIG. 266.—STAGES IN THE EVOLUTION OF THE GREAT LAKES.

drainage. At this stage the ice-dam was still practically continuous along the north-eastern side of the growing

lakes, but in the following stage a further general withdrawal led to the merging of the three western lakes in Lake Algonquin—almost entirely land bounded—and to the uncovering of Lake Iroquois, the ancestor of Lake Ontario.

The St. Croix outlet was now abandoned, but the Chicago and Mohawk overflows continued to function. As regards intercommunication between the western and eastern lakes, two lines were available: (*a*) a short cut from Lake Algonquin to Lake Iroquois *via* Kirkfield and Trent River; and (*b*) a loopway *via* Port Huron and Lake Erie.

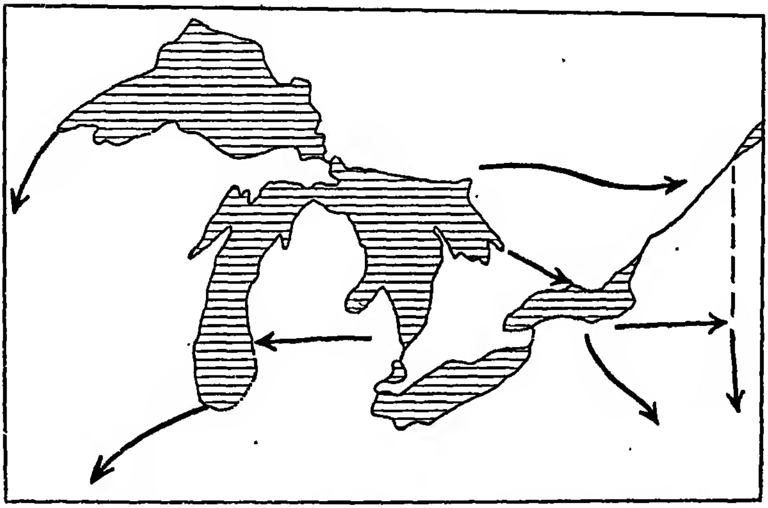


Fig. 267.—Summary of Overflow Routes or Spillways used during Growth Stages of the Great Lakes.

The former functioned in an early stage, but the progressive isostatic recovery of the land to the north following the removal of the ice-load, tipped the balance in favour of the Port Huron route. In the last stages of Lake Algonquin this line had become established, while further ice withdrawal had led to the flooding of Lake Iroquois and the St. Lawrence lowlands by the sea (the Champlain Sea, cf. Yoldia Sea).

The penultimate or Nipissing Stage of evolution is marked by the opening of the great channel from the north-eastern corner of the Huron depression *via* French River and Ottawa River to Montreal. This, in turn, was closed by continuing uplift in the north, which also progressively

excluded the invading sea. The outflow was once again diverted southwards *via* Port Huron and the Erie–Ontario loop.

The nature and extent of isostatic recovery in the Great Lakes region is illustrated in Fig. 268, which shows the attitude of the successive Algonquin beaches and of the Nipissing beach. All the beaches rise in a north-easterly direction, but it is clear that the major part of the warping occurred before the Nipissing Stage.

Some major effects of the Ice Age in the extra-glacial areas.—We have seen that each of the glacial periods must have involved a world-wide eustatic oscillation of sea-level. It will simplify our thinking on this matter if we consider first what the results must have been on the simple assumption that the land, outside the glaciated tracts, was unmoved during the rise and fall of the sea.

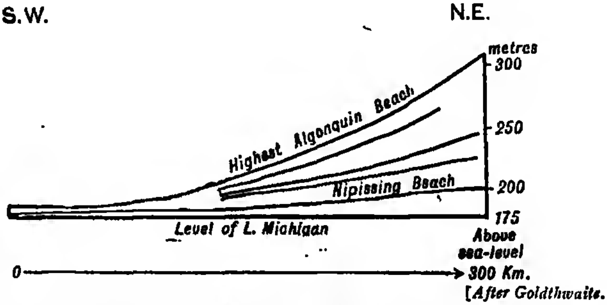


FIG. 268.—PROFILES OF THE SHORELINES ON THE EAST SIDE OF LAKE MICHIGAN, SHOWING EFFECTS OF WARPING.

The high sea-level of the pre-glacial ice-free earth would be marked by a strand-line, though this might be locally obliterated by erosion. The low sea-level of the first glaciation would be similarly engraved on the land margins, but its record would be drowned in the first interglacial period. Assuming that this melting did not involve the complete return of ice-water to the oceans, *i.e.* that upland glaciers persisted through the period, the risen sea-level would not attain to the height of the pre-glacial strands. Following the second glaciation with its low sea-level, the second interglacial period, warmer and longer than its analogues, must certainly have involved an almost complete deglaciation, and we might expect therefore that the sea-level would rise close to the pre-glacial level. The second pair of glacial periods would involve similar oscillations, and since

existing ice-masses represent an ocean layer some 50 metres thick, present sea-level should lie some 50 metres below the highest pre- or interglacial strand-lines.

These explanations, while rendering clear the nature of the problem, accord neither with theory nor observation. The crust did not stand unmoved during these complex sea-level movements. Isostatic and elastic deformation cannot, in the nature of the case, have been confined to the glaciated tracts and their peripheries, though their effects may have been relatively slight in distant extra-glacial areas. Further, the normal processes of earth-movement can hardly have been in complete abeyance during the million years of Pleistocene time. Taking a broader view over a longer period, we are still in the aftermath of the Mid-Tertiary movements, and many parts of the world reveal the plainest signs of continued instability. We should therefore expect to find actual strand-lines and associated features revealing the interaction of crustal and sea-level movement, and nearly all observers are now agreed that the facts warrant such an interpretation. The hope of a rigidly ordered sequence of strand-lines which might provide a simple basis for the study of Pleistocene chronology and physiographic change is quite illusory. The surviving record is complex and, as yet, little unravelled. We may find some satisfaction, however, in the evident truth that, without the complication of earth-movement, all save the highest Pleistocene strand-lines would have been drowned by the last glacial melting.

Let us consider first the simplest case—the evidence of emergence during the last glaciation, followed by the great submergence, which has been called by Dubois the "Flandrian transgression." During the period of low sea-level, many rivers cut deep trenches and large areas of the present shelf seas were dry land. The southern part of the North Sea Basin affords us an excellent instance of the phenomena. Here the Thames flowed north-eastwards across the emergent sea-bottom to join the Rhine, and forests grew widely over the low ground. Such a geography effectively joined Britain to the Continent, permitting the ready passage of plants, animals and man himself (Fig. 269). Similar testimony comes from many other widely separated regions. The stumps of trees rooted in soil occur widely round the coasts of Britain at or below low-water mark—the "submerged forests." Rivers such as the Shannon, the Hudson and many others **reveal**

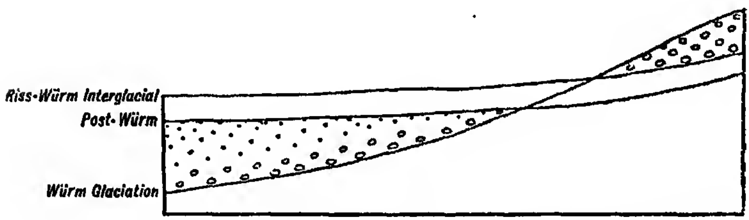
submarine trenches extending seaward of the present coasts. The great Sunda Shelf uniting Sumatra, Java and Borneo represents former land across which stream courses are plainly marked. A study of the depths of the straits separating many continental islands from the mainland, shows that their floor must have been dry land during the last glaciation. This applies to Tasmania and Ceylon; and Asia must have been joined to North America across the narrow and shallow Bering Strait. The floors of the emergent shelf seas provided an ample supply of wind-blown sand, from which the older coastal dunes of many regions (*e.g.* South-west France) were built. Such evidence of former emergence in the coastal areas carries with it the plain corollary of later submergence. The embayed coastlines of the world, the estuaries, rias, and natural harbours attest the great melting, as also do many young and developing cliff-lines, where marine-attack has been recently resumed. The deep trenches cut by the rivers in the emergent phase were filled with alluvia during submergence, and are preserved to-day only as "buried channels."

[*After Reid.*

FIG. 269.—LATE PLEISTOCENE EMERGENCE OF THE FLOOR OF THE NORTH SEA.

There is plentiful evidence of earlier oscillation of sea-level, but correlation of such evidence over wide areas is confronted with grave difficulties and has made, as yet, little headway. As early as 1899 de Lamothe discovered parallel strand-lines, or marine terraces, on the Algerian coast at approximately 100, 60, 30, and 20 metres above present sea-level. He invoked eustatic shifts of sea-level to account for the facts, and showed that the terraces of the Isser, as well as the Somme and the Rhône revealed a similar record. The later work of Depéret and others in the Mediterranean has attracted much attention, since it

went far to establish the reality of the four stages distinguished by de Lamothe. To these names were given: Sicilian, Milazzian, Tyrrhenian, Monastirian; and it was supposed that the stages were correlative in order of decreasing level and age with the four Alpine glaciations. From the standpoint of current theory the physical basis of this correlation involved a curious error, for it was conceived that each marine terrace was linked by a river terrace with one of the Alpine moraines. This implied that the periods of high sea-level were contemporary with the glaciations, an unnatural and unlikely relationship. Baulig has since deduced the probable relationship of the river terraces to the glaciations, and vindicated his deductions by study of certain rivers in Southern France. During glacial times, with increased load, the slopes in the upper reaches of glacial rivers must have been increased by aggradation; while at the same time the rivers cut



[After Baulig.

FIG. 270.—THE LONG-PROFILE OF A GLACIAL RIVER BEFORE, DURING, AND AFTER THE LAST GLACIATION.

back and graded themselves in their lower courses in response to the lowered sea-level. With deglaciation and diminishing load, the rivers must have lowered their slopes upstream, entrenching themselves in their glacial flood-plains, while simultaneous aggradation in the down-stream regions buried the "cut-back" or trenches (Fig. 270). This analysis destroys the basis of Depéret's correlation, and suggests, as we should expect, that the marine terraces correspond to the interglacial periods.

In recent years, the work of Cooke and Antevs in the United States has produced impressive evidence of a flight of marine terraces extending along the eastern seaboard of North America from Florida to New Jersey. The members of the series maintain consistent heights and spacings over long distances, and reveal a succession of events significantly parallel with that of the Mediterranean terraces. There is a 30-metre terrace comparable

with the Tyrrhenian terrace of the Mediterranean, and yielding, like the latter, a warm-water molluscan fauna. Herein lies a suggestive basis for inter-regional correlation, for both in Europe and America there is reason to regard the terrace in question as marking the second or major interglacial period.

In considering the marine terrace sequences of Europe and America, it is essential to remember that since the melting of existing ice-masses would not raise the level of the sea to that of the highest marine terrace, the descending sequence as now preserved cannot be explained by eustatic shifts of sea-level alone. It involves considerable and apparently very uniform uplift of the land, of which the nature and origin is as yet unexplained. Pleistocene strand-lines and marine terraces exist also in other parts of the world (*e.g.* South Africa, Peru), but in the present state of knowledge correlation would be premature. We must rest content with the fact that the expected Pleistocene oscillations of sea-level are plainly demonstrated by coastal forms in many regions, and with the important corollary that river-erosion and deposition must necessarily have been governed by this control for a long period in the recent past.

Coral Islands and Reefs.—Change of sea-level in the extra-glacial areas has also been held accountable for the growth of coral reefs. The problem presented by these structures is specialized and controversial, yet its general importance can hardly be gainsaid when we recall that coral structures afford almost the only accessible portions of the "crust" over large parts of the great Pacific region, and are, therefore, among the chief sources of evidence on which the physical history of the Pacific must be based.

We cannot here pursue what has become a voluminous controversy to its limits, but the main point at issue is readily defined. Reef-building corals thrive only in warm, mud-free waters in which the temperature does not fall below 22° C. Growth does not extend to a depth of more than 20–25 fathoms. If, therefore, coral rock structures exceeding a thickness of 150 feet exist, they can only have come into being through progressive submergence. In the classic theory of Darwin and Dana such submergence was believed to depend on extensive and long-continued subsidence of the ocean-bottom. Upgrowth of corals, keeping pace with subsidence, could thus account for the development in succession of fringing reefs, barrier

reefs and atolls, the three chief recurring types of coral structures in the tropical oceans (Fig. 271). Such a mechanism would result in the presence of great thicknesses of coral rock beneath atolls.

There are geophysical difficulties, not necessarily insuperable, in assuming widespread and simultaneous subsidence of great amount in the ocean-floor, and the difficulties are hardly less great if we have recourse to localized subsidence to explain each individual case. An alternative method of providing the " submergence " is, evidently, to invoke the rise of sea-level following the last deglaciation, though in such case we could not account for thicknesses of coral rock exceeding about 100 metres. The " glacial-control " theory of coral reefs elaborated by Daly makes use of this idea (Fig. 272). It represents coral reefs as essentially

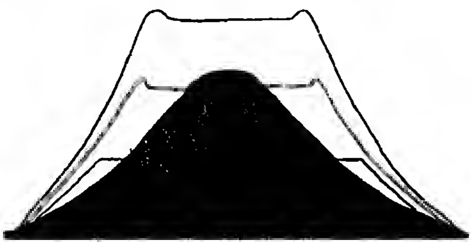


FIG. 271.—ORIGIN OF CORAL REEFS ACCORDING TO DARWINIAN THEORY OF SUBSIDENCE.

Below, fringing reef; passing upwards with continued growth into barrier-reef and atoll.

steep-walled " crowns," built on submarine platforms, which were developed during pre-glacial times, and later smoothed by marine abrasion and sedimentation during the Ice Age. Most existing reefs are regarded as having grown up *pari passu* with the rise of sea-level since the last glaciation, and therefore as not more than 100 metres thick. It is claimed that this theory explains the narrowness and evident youthfulness of the reefs as a whole, their wall-like form and the extraordinarily level nature and accordant depths of lagoon floors over wide regions. The theory does not preclude localized subsidence as an explanation of " drowned " reef structures, nor localized uplift in the case of " emergent " reefs. The latter may also be accounted for by reef building to a higher level during one of the interglacial periods.

The relative merits of the " subsidence " and " glacial

control" theories have been the subject of much discussion, and general agreement is not yet in sight. On the one hand, it has been stated that the thorough reinvestigation of the problem by W. M. Davis "entirely substantiates Darwin's theory and shows the inadequacy of all others." On the other, Daly has shown that several features of the "glacial-control" theory have been misinterpreted by critics. The apparently simple test of boring through coral caps to ascertain their thickness has not yet yielded final evidence. A boring at Funafuti, north of Fiji, passed through 340 metres of coral rock, but the site of the boring was near the edge of the reef, and it is authoritatively stated that not more than 60 metres of the core

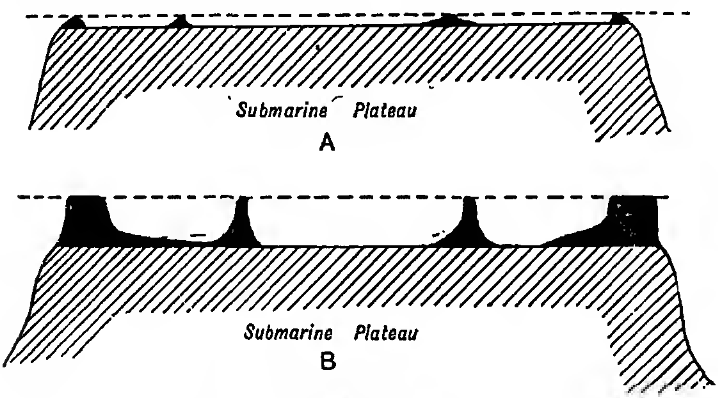


FIG. 272.—ORIGIN OF CORAL REEFS ACCORDING TO GLACIAL CONTROL THEORY.

represented coral rock *in situ*, the rest being essentially talus on the seaward face. A boring at the small reef of Michaelmas Cay, off the Queensland coast, passed through organic material to a depth of 73 metres, where it entered quartz sand. This result is in complete accordance with Daly's theory. It is perhaps unlikely that either of the theories in its simple form is sufficient to account for the whole range of coral-reef phenomena. Certain it is that any theory must allow for the undoubted "glacial" fluctuations of sea-level.

In the foregoing chapter we have covered a wide field in broad outline, concentrating as far as possible on morphological aspects and necessarily leaving much unsaid on the geological side. One cannot too strongly emphasize

the immense complexity in detail of the Pleistocene record and the great amount of research waiting to be done. Nevertheless, the main contributions of the period to the physical geography of the earth are now plainly discernible, and often occupy the forefront of the landscape picture as seen by the geomorphologist and the geographer. Just as the last main formative stage of human evolution—the Industrial Revolution and the Railway Age—has laid its obliterating, and at times disfiguring, hand dominantly on the cultural landscape, so the Pleistocene Epoch "finished" the physical landscape, providing a myriad significant details in scenery and human environment. The Pleistocene Epoch witnessed man's social, if not his physical, beginnings. Since it may have much of its course still to run we can put no ready limits to its future influence on terrestrial scenery and the life of man.

INDEX